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Agricultural technologies for climate change in developing countries: Policy options for innovation and technology diffusion

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ABSTRACT

Climate has obvious direct effects on agricultural production. The reverse is more apparent than ever as greenhouse gas emissions from agriculture are tallied. The development and effective diffusion of new agricultural practices and technologies will largely shape how and how well farmers mitigate and adapt to climate change. This adaptation and mitigation potential is nowhere more pronounced than in developing countries where agricultural productivity remains low; poverty, vulnerability and food insecurity remain high; and the direct effects of climate change are expected to be especially harsh. Creating the necessary agricultural technologies and harnessing them to enable developing countries to adapt their agricultural systems to changing climate will require innovations in policy and institutions as well. Potential constraints to innovation involve both the private and public sectors in both developing and developed countries. The process of transferring agricultural innovations across agroecological and climatic zones is often subject to agronomic constraints. Often, the most binding constraints occur at the adoption stage, with several factors that potentially impede poor farmers' access to and use of new technologies. Based on discussions of these constraints, we derive six policy principles and use these principles to suggest several specific investments and policy priorities.

Introduction

Climate has obvious and direct effects on agricultural production. At a global scale, the reverse is also increasingly apparent. Agricultural activity emits greenhouse gases (GHG) through use of fossil fuel-based inputs and equipment, livestock production, soil erosion, and land conversion and deforestation. Agriculture directly accounts for 14% of global GHG emissions in CO_2 equivalents and indirectly accounts for an additional 17% of emissions when land use and conversion for crops and pasture are included in the calculations (IPCC, 2007; World Bank, 2009). Accordingly, the climate change agenda has subsumed agricultural production as both a contributor to climate change and, through adjustment in practices, a potential mitigating force (e.g., Khan et al., 2009). Climate change and climate policy will have potentially significant impacts on agriculture by shaping what products and practices are most suitable in each location. We contribute to recent and related research (e.g., Nelson, 2009; Seo, 2010) by describing the potential role innovative agricultural practices and technologies can play in climate change mitigation and adaptation and asking: What policy and institutional changes would encourage the innovation and diffusion of these practices and technologies to developing countries?

Research and innovation have been central to agricultural policy for nearly two centuries, often with the goal of increasing output per unit of land, water, labor or other input. Reducing negative environmental impacts and improving micronutrient density are more recent agricultural research objectives. With climate issues adding to this already challenging agenda, the need for agricultural innovation has never been more apparent. These climate concerns are both shaping research priorities and rekindling the impetus for investments in agricultural research (Howden et al., 2007). In the coming decades, the development and effective diffusion of new agricultural technologies will largely determine how and how well farmers mitigate and adapt to climate change. This adaptation and mitigation potential is nowhere more pronounced than in developing countries where agricultural productivity remains low; poverty, vulnerability and food insecurity remain high; and the direct effects of climate change are expected to be especially harsh.

Developing countries are particularly vulnerable to climate change because they depend heavily on agriculture, tend to be hot already, lack infrastructure to respond well to increased variability, and have limited capital to invest in innovative adaptations (see Barrios et al., 2008). To wit, whereas the Stern report (Stern,

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2007) projected that a 2 °C increase in average temperatures would reduce world GDP by roughly 1%, the 2010 World Development Report of the World Bank (2009) estimates that without offsetting innovations climate change would ultimately cause a 4% and 5% decrease in (baseline scenario) GDP for Africa and India, respectively. While climate change may reduce global agricultural production by 6% by 2080 from what would otherwise occur, Africa and India are projected to see reductions of agricultural output by 30% or more (Cline, 2007).[1] In 2080, we will likely produce more food than we do now, but it will likely be more expensive compared to other goods. This will hurt the urban poor and any remaining poor farmers who are still net food buyers. The political tensions and urban pressures associated with these vulnerabilities and attendant economic transformations could be particularly problematic.

Agricultural technologies for mitigation and adaptation

The core challenge of climate change adaptation and mitigation in agriculture is to produce (i) more food, (ii) using fewer resources, (iii) under more volatile production conditions, and (iv) with net reductions in GHG emissions from food production, processing and marketing. As long as climate change and the policy responses it induces do not interrupt long-term income growth or alter the long-term decline in relative food prices so much that the path towards improved diets is reversed, aggregate food demand will continue to grow along with population and income growth. As climate change affects input availability, especially water in many places, input use efficiency must increase with these productivity demands. Carbon emission polices may simultaneously encourage producers to recognize GHG emissions as a costly production input and create new opportunities and incentives for on-farm GHG mitigation. Producers will grapple with these growing demands and shifting incentives amidst more volatile production conditions. Agricultural technologies will play a central role in enabling producers to meet these core challenges.

Because agriculture is inseparably linked to climate and feedback runs in both directions, most agricultural technologies have direct or indirect climate linkages. Most new technologies change the use of farm inputs, often in ways that alter the impact of weather on production and of production on carbon emissions. While most agricultural technologies therefore have climate implications, there are a handful of current and emerging technologies with particular relevance to developing country agriculture and climate change. Some of these technologies have straightforward connections to climate change, but for others these connections are more nuanced. Below, we highlight some relevant technologies or technology categories, which we will use as a platform for exploring the policies and institutions necessary to support the development and diffusion of current technologies – and to provide incentives for technological breakthroughs in the future.

New traits, varieties and crops

Increasing agricultural productivity requires technological advances in crop yields. In contrast to developed counties, which have seen dramatic yield gains in the past century through investments in agricultural innovation and operate close to the technological frontier, much of developing country agriculture is far from this frontier. Thus, the greatest latent productivity potential resides in developing countries and especially Sub-Saharan Africa, which has cereal yields that are half or less of the rest of the world. In these places, profitable adaptation and farmer adoption of suitable varieties and crops could spark substantial yield gains. These productivity gains could confer a substantial mitigation benefit in the form of foregone land conversion or even reversion of some sensitive lands to grass or forests. Since land use changes, deforestation and conversion to agricultural production account for 17% of global CO_2 emissions (World Bank, 2009, Chapter 3, p. 16), productivity gains represent a significant mitigation mechanism in agriculture. New varieties and traits can also lead to less intensive use of other inputs such as fertilizers and pesticides and the associated equipment.

In addition to increasing productivity generally, several new varieties and traits offer farmers greater flexibility in adapting to climate change, including traits that confer tolerance to drought and heat, tolerance to salinity (e.g., due to rising sea levels in coastal areas), and early maturation in order to shorten the growing season and reduce farmers' exposure to risk of extreme weather events (e.g., Karaba et al., 2007). These promising new traits and varieties, which are mostly still in development, can emerge from traditional breeding techniques that leverage existing varieties that are well suited to vagaries of the local production environment as well as from more advanced biotechnology techniques such as marker assisted selection and genetic modification.

Climate change will also lead to new pest and disease pressures. The nuances of temperature changes – e.g., higher low temperatures and fewer freezes – could shorten dormant periods, speed pest and disease growth and change the dynamics of these populations and their resistance. Crops, varieties and traits that are resistant to pests and diseases will improve producers' ability to adapt to climate change. To the extent that these varieties also reduce the need for pesticides, they also reduce carbon emissions by decreasing pesticide demand as well as the number of in-field applications. However, since a substantial proportion of the GHGs produced by agriculture are attributable to the production and application of nitrogen fertilizer, breakthroughs in nitrogen use efficiency could substantially mitigate emissions in agriculture.

Biotechnology stands out as a promising set of tools to facilitate the development of traits and varieties that could help to mitigate and adapt to climate change (Fedoroff et al., 2010). While controversial in some policy arenas and public fora, agricultural biotechnology has produced dramatic improvements in yield and reductions in production costs and input use intensity, especially pesticides and herbicides. Many of the promising traits and varieties discussed above owe their existence to biotechnology, including genetically modified crops with pest resistance (Bt) and herbicide tolerance (RoundupReady) and conventionally bred varieties that benefit from breeding tools such as marker selection and tissue culture. The drought and salt tolerant traits that are beginning to emerge are largely the product of biotechnology, including the Water Efficient Maize for Africa project[2] and other partnerships between public research institutes and private agricultural biotechnology firms such as Monsanto. Genetically modified crops have raised yields and reduced GHG emissions by reducing demand for cultivated land and fossil fuel-based inputs. These reductions are most direct in the case of Bt crops, which require fewer pesticide sprays. In 2007 alone, a year when GM crops were grown on only 7% of arable land in the world, the total reduction due to both the direct and indirect emission effects of GM crops amounted to over 14,200 million kg of CO_2 – the equivalent of removing over 6 million cars from circulation (Brookes and Barfoot, 2009). Herbicide toler-

[1] Modeling the possible impacts of climate change on agricultural production is wrought with challenges. While different assumptions and approaches can change these impacts, contrasting and comparing these approaches is not the focus of this paper. In addition to Cline (2007), which has some known weaknesses, we point interested readers to a few other influential studies on the topic (e.g., Fischer and Shah, 2005; Mendelsohn, 2000, 2007).

[2] See http://www.aatf-africa.org/userfiles/WEMA-brief.pdf (accessed 11 October 2011) for more details.

ance can further reduce emissions enabling changes in production practices – e.g., by making reduced- or no-till systems, which reduce soil erosion and hence carbon emissions, more cost effective (more below).

Water management and irrigation

Across the Middle East and North Africa, Central Asia and Southern Africa, water availability is projected to decline dramatically with climate change and population growth in the next several decades. In the midst of increasing urban and environmental demands on water, agriculture must improve water use efficiency generally. With hotter temperatures and changing precipitation patterns, controlling water supplies and improving irrigation access and efficiency will become increasingly important. Climate changes will burden currently irrigated areas and may even outstrip current irrigation capacity due to general water shortages, but farmers with no access to irrigation are clearly most vulnerable to precipitation volatility. Since Africa only irrigates 6% (13.6 million hectares) of its arable land in contrast to 20% worldwide (FAO, 2010), African farmers are in desperate need of techniques, technologies and investments that improve water management efficiency, access to irrigation or to find ways to improve incomes with less secure and more variable water availability. It is no exaggeration that the future of agriculture in these regions hinges primarily on improving the efficiency of existing irrigation systems and, where profitable, extending irrigation infrastructure. Drip irrigation systems are important on farmers' fields, but inefficiencies in delivery (e.g., canal construction and maintenance) are often more glaring than field-level inefficiencies in application (e.g., flood versus drip irrigation). Even with these improvements, water scarcity may end agricultural production in some marginal areas, leading to permanent depopulation.

In places with limited access to irrigation, well-timed deficit irrigation can make a substantial difference in productivity. With dwindling water supplies, such deficit irrigation techniques will become increasingly important. In non-irrigated areas, water conservation and water harvesting techniques may be farmers' only alternative to abandoning cultivation agriculture all together. Adopting such practices may not be technology intensive, but will almost certainly require investments in capacity building and agricultural extension. Furthermore, in some places, such investment simply will not pay and investments in helping the population to prepare for other occupations in other regions may be the appropriate course.

Whether a particular zone expects to become wetter or drier on average in the coming decades, water management is central to farmers' adaptation to climate change. Expansion and improved efficacy of water storage is fundamentally important to account for increasing rainfall intensity and longer stretches of dry days around the world. In addition, where agriculture relies on snow pack for early season storage, changes in the timing and form of precipitation place added emphasis on the need for improved water management and storage.

Other production inputs

Improvements in crop yields per unit of land are crucial as an alternative to extensive conversion of grassland and forestland to crops. Therefore practices or technologies with potential to increase the intensity of land use can yield mitigation benefits. This may even include application of additional fertilizer or pesticide inputs, where the first round GHG implication may not look favorable. There are, however, other amendments such as biochar, a charcoal soil amendment, that may offer both improved soil fertility and serve as a carbon sink (Lehmann et al., 2006). Similarly, herbicides and other inputs that reduce competition from weeds can improve productivity and thereby serve to mitigate GHG emissions associated with bringing additional land under cultivation. Furthermore, since potential cropland in different regions has very different capacities to sequester carbon, shifting crops to the land with the least negative carbon implication may have net GHG benefits. This may mean farming dry regions under irrigation which allows use of land that otherwise would not contribute to mitigation.

Production management and practices

Production techniques may be as important as production technologies in climate change adaptation and mitigation. Since soil erosion is a major contributor to agricultural carbon emissions (see Lal, 2011 for a recent review), conservation or reduced tillage agriculture stands out as a potentially potent improvement over conventional practices. This technique aims to build up organic matter in soils and create a healthy soil ecosystem by not tilling the soil before each planting. Seeds are planted using seed drills that insert seeds to a precise depth without otherwise disturbing the soil structure. By increasing the organic matter in soils, conservation agriculture improves the moisture capacity of the soil and thereby increases water use efficiency. The practice also reduces carbon emissions by reducing tilling, although it also requires more sophisticated pest and disease control because the system is not 're-booted' at each planting (Hobbs and Govaerts, 2009).

An array of other production management practices and technologies could similarly improve farmers' mitigation and adaptation to climate change, including equipment and information that enables more precise application of inputs, especially fertilizer. In flood irrigated systems laser land leveling can improve water use efficiency, reduce reliance on diesel pumps, and provide strong productive complementarities with conservation agriculture (Jat et al., 2006). Intercropping of trees and annual crops – so-called Evergreen Agriculture – appears promising in some semi-arid locations as a means of protecting and amending the soil (Garrity et al., 2010). As with all technologies that seem useful, these practices must not reduce yields – otherwise the demand for additional land might offset benefits from on-field sequestration.

Marketing and supply chains

Whereas this paper considers mainly farm practices and technologies, the potential for GHG mitigation after products leave the farm are also crucial. It is well known that transportation is a major contributor of GHG emissions. Post harvest GHG emissions per unit of consumption mainly depends on efficiencies of transport (rail versus road, ocean shipping versus land shipping, and large loads versus small load) rather than distance traveled. Improvements in transportation efficiency are therefore as important to reducing agriculture's GHG emissions as they are to other sectors of the global economy. Although local food production is currently a fashionable response to the GHG emissions attributable to shipping food, in many cases the greatest net reduction in GHG emissions may come from producing crops where they can be grown most efficiently and investing in improved efficiency transport to move the food to consumers.

Post harvest losses represent one of the single greatest sources of inefficiencies in food production worldwide and therefore one of the best opportunities for effectively improving crop productivity. These losses – which are due to poorly timed or executed harvesting, exposure to rain, humidity and heat, contamination by microorganisms, and a host of other sources of damage and deterioration – often get far less attention than they deserve. Half or more of the total harvest of some crops can be lost post harvest.[3] Investments in improved harvesting, processing, storage, distribution, and logistics technology and necessary training investments can pay off as well as improved crop yields in terms of gains to consumers and the climate. As climates become hotter and precipitation more erratic, the potential for post-harvest losses may increase and thus improved transport and storage become even more important.

Information

As farmers and others deal with changes in climate and more variability in weather, history becomes a less reliable guide. Under these conditions there is greater payoff to improvements to forecasts of weather events and inter-seasonal weather probabilities. For example, warmer ocean temperatures are likely to make *el niño* events more frequent and severe. Farmers with foreknowledge of such events can respond by planting more appropriate crops or varieties (say barley rather than maize if a dry year is expected.) Such improved forecasts would also affect planting even in regions unaffected by the weather events in response to price expectations and opportunities for trade. Furthermore, intertemporal arbitrage in the form of storage or forward contracting would be used to offset changes in expected harvests. Thus major innovations in response to climate variability will take the form of improved information through global monitoring and forecasting (Hallstrom and Sumner, 2000, Sumner et al., 1998). Improved micro-climate modeling can also enable more accurate interpolations between actual weather stations and, in effect, create virtual weather stations for nearly any location. These improved interpolations could lead to improved short term forecasts, which could be disseminated via text messages using rapidly spreading cell phone networks. Lastly, better and more timely information can also help to forecast impending 'slow onset' weather events such as drought more effectively and thereby improve response times and adaptation (Mude et al., 2009a).

Insurance

Innovations in microfinance generally and in micro-insurance products specifically may aid farmers' capacity to adapt to climate change, especially in settings that will experience greater variability and more frequent extreme events. Compared to microfinance, micro-insurance innovation and availability is much more limited – although potentially just as important (Alderman and Haque, 2007; Barrett et al., 2007). Although traditional crop insurance in developed countries has required heavy subsidies to maintain widespread use of multi-peril (e.g., rainfall, hail, drought, pests, etc.) insurance (Glauber, 2004), many hope for more promising results with index insurance in many developing countries. These index insurance products are based on an index that correlates strongly with farmers' production outcomes and that is commonly constructed based on remote sensing data, which limits traditional adverse selection and moral hazard problems and reduces administration and monitoring costs (Dischel, 2002; Hess et al., 2002). Although the impetus for these efforts has primarily come from the public sector development community, private banks and re-insurance firms are actively involved. In arid pastoral settings, index insurance based on measures of greenness from satellite imagery can proxy for rangeland quality (and, by extension, the herd and livestock mortality risk). Such a livestock index insurance product could protect against severe drought losses, will soon be available to East African pastoralists and appears to be promising (Mude et al., 2009b). While the herders themselves are the target clientele of this product, there is substantial interest in the product among NGOs and humanitarian agencies that hope to use index insurance not to insure against livestock mortality per se but to ensure that they have financial resources on hand to more quickly mobilize famine relief efforts in the region.

While the innovation frontier for index insurance products is expanding quickly and these products appear to improve agricultural producers' capacity to adapt to climate change, a few limitations are worth noting (Skees, 2008). First, getting these products to smallholders may be difficult and costly. Demand for insurance among isolated smallholders may be weak because the products are difficult to understand or are not adequately correlated (negatively) with their main sources of risk. Delivering the products to smallholders may be especially costly due to administration costs (e.g., the cost of preparing, processing and delivering relatively small indemnity checks to smallholders with small insurance policies can be prohibitive). In many settings, it may therefore be more effective to target financial or humanitarian intermediaries as the primary clientele for these index insurance products. Financial intermediaries with protection against extreme weather events should be more willing to provide services to producers who are directly vulnerable to these extreme events. NGOs and other humanitarian intermediaries may be able to respond more quickly to localized food production shortfalls (Chantarat (Chantarat et al., 2008) – an important improvement given that delays in response time continue to be the most important impediment to effective food aid responses. Second, the current generation of weather index insurance products are designed for simple production environments that are heavily driven by a single weather outcome. In more complex, diversified production settings, a much broader set of weather events matter to production outcomes, including cumulative rainfall, extreme temperature or rainfall events, wind events, etc. Furthermore, the impact of the timing of these events on production varies widely across crops, which is precisely the diversification benefit. Designing an index product that reflects a broad set of relevant weather events and the diversification of household productive activities is challenging, but also necessary if micro-insurance is to help smallholders in tropical developing countries adapt to climate change.

Innovation and diffusion considerations

This section describes impediments to the innovation and diffusion of agricultural technologies such as those above that could help producers mitigate or adapt to climate change. It also offers some discussion of potential remedies to these impediments. Together, these constraints and potential remedies set the stage for exploring the policy responses necessary to support the development and use of these technologies. While the section builds on the set of technologies described above, many of the considerations we describe are also relevant to the innovation of new technologies that have yet to be conceived.

Innovation considerations

Potentially important impediments to innovation exist at multiple levels. Growth in public sector agricultural R&D has lagged in recent decades with disconcerting impacts on productivity gains (Alston et al., 2009). For example, growth of US public spending on agricultural R&D has fallen to 0.8% per year from about 2.2% for the whole period since 1950 (Alston et al., 2009). This general trend in declining growth rates in public investments in agricultural R&D broadly constrains the innovation of technologies related to climate change, but tends to fall heaviest on developing

[3] For a complete discussion and other resources on post harvest losses in Africa, see http://www.phlosses.net/.

countries that rely heavily on public agricultural research. These countries tend to depend importantly on the resources and research of the Consultative Group for International Agricultural Research (CGIAR). As an extension of efforts that had begun in the 1940s and expanded through the 1960s, the CGIAR system of centers grew rapidly, but budgets have become more constrained as the perceived mission of these centers expanded past productivity growth. While large countries such as China, India and Brazil, which account for hundreds of millions of farmers, have relatively strong domestic research capacity in agriculture, most developing countries – including most of Africa – have weak capacity and limited resources and infrastructure for conducting useful research (Pardey et al., 2006). Promising efforts to develop local R&D capacities in the past have been squandered by a lack of continuity and sustained investment. Constrained local capacity has limited the ability to adapt new traits and varieties to local conditions. As a cumulative effect of the slowing in public investments in productivity-enhancing innovations, the rate of agricultural productivity growth has diminished and the flow of innovations tailored to the agricultural production conditions in poorest countries has slowed (Alston et al., 2009).

Innovation constraints in many developing countries stem from deeper problems in the agricultural sector. Many of these countries have a long history of substantial and direct government involvement in both input and output markets in agriculture. This legacy often creates static and bureaucratic seed sectors, for example, which can stifle the formation of vibrant private firms and accompanying incentives to innovate. There are notable exceptions, including India where a dynamic private seed sector thrives and faces clear incentives to innovate in ways that matter to their demanding clientele (which commonly include even the smallest of smallholders). More broadly, developing countries' research capacity and resources in agriculture are typically not managed in response to innovation incentives. Indeed, their capacity and resources are limited in part because of the absence of a seed sector that relays clear market incentives.

Other institutional constraints can hamper innovation. For more advanced technologies, for example, the level of intellectual property (IP) protection in developing countries can have an impact on R&D investments. Combined with their own weak research capacity, this constraint can create 'orphan crops' that suffer from the lack of attention from private firms and the lack resources and capacity from the international and domestic public sector. Although some have proposed creative remedies to this constraint such as offering research prizes (Masters, 2005), the diversity and complexity of agriculture may pose challenges to such remedies even if similar approaches are workable in the pharmaceutical industry.

Arguments for public funding of agricultural research often hinge on the broad benefits of enhanced agricultural productivity and the public goods associated with this research in the form of new knowledge, products or services. This argument may apply to public agricultural R&D funds for climate change mitigation and adaptation. As long as carbon is not incorporated into pricing, however, there will be insufficient incentives to develop and adopt agricultural technologies that may mitigate climate change. Putting a price on carbon would create incentives for private research and innovation in agricultural technologies and practices. Creating functional carbon markets that can incorporate the full GHG impacts of agricultural practices or technologies is a challenging endeavor. Measuring carbon credits associated with changes in agricultural practices or technologies can be particularly difficult. For example, a practice that reduced fertilizer use at the expense of lower yields may reduce emission for the affected field but may increase global emission as foregone productivity is replaced by opening new land in another location. Likewise, credits for practices specific to one crop may attract land from cropping systems that have lower GHG emissions. Current efforts to measure these emission changes tend to ignore market implications, a fatal flaw that may create false carbon credits for changes in practices or technologies that actually increase rather than decrease GHG emissions. While functional carbon markets may create more socially efficient incentives for agricultural innovation, getting these markets to properly convey these incentives will require more sophisticated and comprehensive carbon measurement.

Transfer considerations

Since developing countries rely on agricultural research conducted internationally, they also rely on the international transfer of new technologies and research tools. Such transfers are often subject to agronomic and agroecological constraints. For the classic constraint of this sort – new varieties and crops must be suitable to the growing conditions of a particular locale before it can be successfully introduced – the distinction between early 'upstream' research and later, more location-specific 'downstream' research stages is important. Upstream research, including breeding lines and breeding techniques and equipment, is often relevant across a wide range of crops and varieties and therefore relatively transportable. Downstream research, in contrast, often requires substantial investments to resolve location-specific problems and develop varieties for local growing conditions. Transfer constraints are more likely to pose problems at downstream research stages. Thus, while many developing countries can in-principle benefit from upstream international agricultural research, limited local research capacity can make it difficult to capitalize on this global stock of agricultural research in practice.

There are natural spillovers between similar agroecological zones. Sharing similar growing conditions with a country with cutting-edge research capacity and resources can remedy many agronomic transfer constraints. In this respect, Africa suffers from a wide diversity of agroecological zones that require substantial modification of promising varieties developed elsewhere, which can limit both technology diffusion and the returns to agricultural R&D (Wood and Pardey, 1998). Agricultural biotechnology has changed plant breeding in ways that relax some of these agronomic constraints. Breeders can now transfer and insert new crop traits with near surgical precision. These techniques can streamline the process of adapting varieties for local conditions, but they can also raise a new set of potential impediments in the form of biotechnology regulations and IP constraints. A lack of biosafety regulations in developing countries, in addition to restrictions on GM crops emanating from developed countries, have made it difficult for developing countries to take advantage of new downstream technologies. Overly restrictive GM crop regulations obviously constrain downstream research stages, including the release and diffusion of new traits and varieties, but so can ill-defined intellectual property rights (Blakeney, 2009).

Recently, some have drawn parallels between the patents and access to medicines debate[4] and the transfer of climate change technologies to poor countries. Indeed, IP-related discussions in the UN Framework Convention on Climate Change (UNFCCC) have borrowed

[4] The role of patents as a potential impediment to access to essential medicines in poor countries has received substantial attention in a host of venues. In 2001, the WTO addressed this issue, in the Doha Declaration on TRIPS and Public Health, by reiterating and expanding slightly the built-in flexibilities of the TRIPS Agreement. These flexibilities, allow countries, among other things, to issue compulsory licenses in order to promote access to medicines that are deemed critical to resolving "national emergencies". The Declaration leaves to each Member "the right to grant compulsory licenses and the freedom to determine the grounds upon which such licenses are granted" as well as "to determine what constitutes a national emergency or other circumstances of extreme urgency".

many of the same arguments and created similar battle lines and alliances as the essential medicines debate. On the one hand, a number of developing countries and NGOs have advocated the use of the flexibilities available within TRIPS to enhance technology transfer of climate friendly technologies to developing countries. On the other hand, many technologically advanced countries and business associations consider that strengthened intellectual property rights play an essential role in encouraging the innovation, transfer and diffusion of climate friendly technologies. Despite these apparent parallels, the role of patents in impeding access to agricultural technologies in general and those related to climate change adaptation or mitigation is more subtle. Agroecological diversity and the other transfer constraints discussed above imply that agricultural technologies cannot be popped like pills with the same effect anywhere. Consequently, countries are less likely to issue a compulsory license for a patented agricultural technology because removing barriers to technology transfer is not just a matter of navigating patent rights.

That the link is more subtle does not imply that IP issues do not matter in agricultural technology transfer. Rather, IP constraints are often less direct in agriculture than in health. Patented research tools or protected varieties and breeding lines technically constrain upstream as well as downstream research, but associated problems have tended to emerge only late in the process. The development of Golden Rice and the complexity of ownership and control of the technology clearly showcased these concerns. In 2000, a detailed analysis of the intellectual property dimensions to the development of Golden Rice documented that roughly 70 patents and patent applications were implicated in the development of Golden Rice (Kryder et al., 2000). Although a patent 'thicket' of this size could be difficult or impossible to navigate in order to get 'freedom to operate' (Heller and Eisenberg, 1998), it ultimately did not pose serious problems because Golden Rice was intended to be distributed to relatively poor farmers in poor countries. This intended use facilitated the negotiations with patent holders in two ways. First, many of the 70 patents that were implicated in the technology were not effective in poor countries. Indeed, many poor countries had no patent restrictions on Golden Rice at all because the inventors had not sought patent protection in small poor countries (and as a matter of practice often do not). Second, there was essentially no overlap between the target clientele of Golden Rice (poor farmers) and the target clientele of the commercial patent holders. This created substantial scope for humanitarian use negotiations, which ultimately defined the humanitarian use market as those farmers in selected developing countries earning less than $10,000 per year from farming (see Lybbert, 2002 for discussion of humanitarian use licensing).[5]

While the willingness of patent holders to negotiate was certainly elevated by the high profile and almost symbolic status Golden Rice had achieved, it nonetheless catalyzed careful thinking and institutional innovation that will benefit lesser technologies with lower profiles for years to come. In particular, it created an institutional framework for resolving intellectual property issues related to access to technologies among the poor through humanitarian use licensing (Lybbert, 2002) and various patent pool arrangements. Patent pools have a history among private firms (Lerner and Tirole, 2004) and have recently emerged as a potentially promising mechanism for facilitating the licensing of technologies within the public sector and between the public and private sectors. However, implementing patent pools in practice, especially in developing countries, can face numerous challenges, which merit careful consideration and further research (Cannady, 2009). A host of other potential remedies for IP issues with climate change technologies more broadly – including the built-in flexibility of the TRIPS Agreement of the WTO – have been explored elsewhere (ICTSD, 2009; Maskus, 2009). Consider two agricultural examples.

First, the Public Intellectual Property Resource for Agriculture (PIPRA) was conceived in the wake of efforts to understand the IP implications of Golden Rice and is supported by a consortium of over 50 institutions in 15 countries. As a consortium of public sector and non-profit institutions, PIPRA offers a variety of services – partly via a network of pro-bono attorneys – that aim to facilitate access to public innovations, especially among the poor in developing countries. PIPRA's services include IP analysis and training, commercialization strategies, drafting and negotiating licensing agreements, and structuring public–private partnerships.[6] Second, the African Agricultural Technology Foundation (AATF), which was similarly conceived in the wake of the Golden Rice case, aims to reduce frictions in the transfer of agricultural technologies to smallholder farmers in Africa by linking private and public sectors. AATF plays a lead role in the WEMA project described above. Of course, public–private institutional innovations such as these face serious challenges and frequent dysfunction, particularly where governance, enforcement and institutional capacity is relatively weak (Poulton and Macartney, in press). Nonetheless, initiatives such as PIPRA and AATF have created a meaningful space in which these challenges can be addressed in the context of agricultural technologies and climate change as experiences accumulate in the coming decades.

These institutions have emerged in part because the complexity and diversity in agriculture effectively segments markets for agricultural technologies. This segmentation between poor farmers in developing countries and rich farmers elsewhere can make public–private partnerships a low risk proposition for private firms and implies that royalty-free, humanitarian use licensing may not pose a threat to firms' profitable, royalty-bearing markets. With some of the climate change technologies discussed above, however, the segmentation between profitable and humanitarian use markets is likely to be less tidy. Many of these technologies may be less sensitive to agroecological conditions than traditional crop varieties can be. For example, biotechnology techniques can facilitate breeding traits into may local varieties, and capacity to use these techniques continues to spread among agricultural research hubs in several developing countries. This highlights a key tradeoff: with less location-specificity, agroecological differences may matter less to technology transfer, but these fading differences also make it more difficult to cleanly segment profitable and humanitarian markets – and legal IP constraints may become more binding as a result. More broadly, the segmentation between these markets will blur as a result of continued economic development in many of today's developing countries. In the process, some of today's poor farmers will gradually emerge from poverty, increase their investment in inputs and technologies, and become important clients to private agricultural firms. This may increase disparities among farmers in poor countries and make it more difficult to segment an entire poor country as a humanitarian use market.

Despite the conventional rhetoric these IP related concerns involve much more than royalties. While the distance and differences between market segments provide a useful point of departure for negotiations, broader technology stewardship concerns – ranging from liability, biosafety, technology management, and public relations – must also be addressed. Successful negotiation of partnerships, preferential licensing terms, or other cooper-

[5] For a case study of Golden Rice and intellectual property negotiations, see http://www.iphandbook.org/handbook/case_studies/cs03/.

[6] In conjunction with the Center for the Management of Intellectual Property and Health Research and Development (MIHR), PIPRA published a valuable online handbook of best practices that is specifically aimed at improving access to agricultural and health technologies in developing countries (see http://www.iphandbook.org/) and provides sample licensing agreements with humanitarian use terms.

ation often hinges more on these stewardship concerns than on royalty concerns. The past decade has stimulated some creative institutional innovation to remedy some agricultural technology transfer constraints. Initiatives such as PIPRA and AATF, though useful, also have inherent limitations. Inevitably, new technologies will continue to demand novel thinking about IP arrangements that encourage greater access by the poor. Demands of new technologies and continued economic development will require further innovation on this front.

Access and use considerations

Even after promising technologies are developed, modified to local conditions, and offered to farmers in poor countries, several factors can impede access to and use of these new technologies. Many of these constraints share the same source as the innovation constraints as described above. In particular, static and poorly functioning input markets, including very limited private sector investment and involvement in the seed sector, can severely limit farmers' access to new varieties. A dysfunctional or unresponsive input sector not only hampers private sector innovation incentives, but can also act as a weak link in the delivery of new technologies developed by the domestic or international public sector. Similarly, poorly integrated output markets can discourage farmers from adopting more productive technologies by reducing transmission of price signals, inhibiting shifts to new crops and introducing substantial market risk. The lack of carbon pricing prevents farmers from internalizing reductions in GHG emissions and may likewise discourage the adoption of new technologies or practices that mitigate climate change.

Improving access is not simply a matter of eliminating the frictions that constrain markets, however, since public coordination and public institutions will continue to play a vital role in testing and adapting appropriate technologies to local conditions. Furthermore, even functional markets are unlikely to create incentives for adaption or adoption in the absence of public goods such as infrastructure, institutions for contract enforcement, and basic sanitation and public health facilities. Thus, the state and strength of local institutions and infrastructure often directly shape farmers' access to and use of new technologies – frequently in ways that weaken innovation incentives and limit the two-way information flow between researchers and farmers. For example, inadequate or ineffective applied research extension systems in some countries seriously limit the spread of new techniques and technologies. While information from input providers, local growers' associations and cooperatives can help to remedy these problems by building farmer networks and facilitating training, these can also raise difficulties of their own. Physical infrastructure such as roads and other transportation and communication networks can affect the dissemination of both technologies and ideas. High transaction costs associated with supplying credit or insurance can discourage the adoption of new technologies as well. Similarly, government management of agricultural output markets can stifle growers' ability or incentives to adopt new varieties and crops. When relevant market prices are not conveyed effectively to farmers, they often lack direct incentives to adapt to new market conditions and continue to cultivate traditional crops or varieties even when more profitable opportunities emerge. As climate change makes dynamic responses to new opportunities and market signals more important, the costs of output market rigidities become even higher.

Even when input and output markets are sufficiently flexible and local institutions and policies are appropriately and sufficiently supportive, other potential access constraints can be relevant. The adoption of some technologies and techniques – particularly those that confer stochastic or intertemporal benefits – involves a complex evaluation process for farmers. Consider, for example, the introduction of a new drought tolerant maize variety to African farmers. Compared to the same variety without drought tolerance, such a variety would reduce losses during drought but be indistinguishable otherwise. Too severe a drought can also eliminate any benefits associated with the drought tolerant variety. Stochastic relative benefit stream such as this are notoriously difficult for breeders to assess and even tougher for farmers to evaluate given their relative lack of control over other production factors (Lybbert and Bell, 2010). In contrast, early maturation, a trait that can reduce a farmer's drought risk in the late growing season, is observable nearly every season and is therefore easier to evaluate.

Access and use constraints often differ across farms. Many of the above constraints are particularly severe for farmers with few livelihood alternatives and high vulnerability to climate change. Small farms often are typically less integrated in both input and output markets and lack access to financial markets and services because transaction costs are high. In some regions, small farms are also subject to more unpredictable growing conditions, which can hamper their ability to assess the value of new seed technologies – making them an unviable clientele for private seed companies. Adoption of innovations by these growers tends to lag because there are simply too many production factors out of their control for farmers to observe how a new variety is different or better than the old one.

Policy and institutional principles and priorities

In the diffusion of existing technologies and the discovery of new ones, institutions and policies are important at multiple scales – from the inception and innovation stages to the transfer of technologies and the access to agricultural innovations by vulnerable smallholders in developing countries. Since cutting-edge agricultural technologies often emerge in developed countries, the institutional research capacity, human capital stock, innovation incentives and policies of wealthy regions typically set the global pace in agricultural innovation. Within developing countries, research and innovation capacity is similarly critical because applying new agricultural technologies generally requires careful and creative modification to reflect local agroecological and production conditions. National and local conditions are critical, including the structure and degree of integration of local input and output markets, the quality of infrastructure, and access to information and effective agricultural extension services. Policies and institutions that relate to market structure, intellectual property rights, and investments in education, training and research capacity directly shape both the creation and diffusion of new agricultural technologies – many of which can help farmers mitigate or adapt to climate change.

In this section, we explore potential improvements in policies and institutions that could contribute to these development and diffusion processes, which take on new urgency under pressure from climate change and climate policy. As a complement to other efforts to draw policy lessons from improved understanding of climate change and agriculture linkages (Nelson, 2009), we begin by outlining several principles that should guide the formulation of new or modified policies and institutions that aim to stimulate more rapid innovation, transfer and adoption of relevant agricultural technologies. We then build on these principles and offer several specific policy options that merit careful consideration.

Policy and institutional principles

Policy and institutional reform should enhance information flows, incentives and flexibility

With changing climates and changing policy environments, information for better decision making is crucial for growers, upstream suppliers and downstream marketers. Signals from prices and accurate price expectations determine the efficiency of responses to changing incentives. The more incentives reflect true costs and benefits, the more agricultural responses will correspond to needed adaptation and mitigation. Of course, flexibility to respond is also required, and the flexibility premium is all the more important when climate and economic environments are changing.

Policies and institutions that promote economic development and reduce poverty often improve agricultural adaptation

When conditions are static, there is little premium to the ability to deal with change. Under dynamic and variable conditions, however, the individual and social payoff to being better able to deal with disequilibrium is substantial. The effectiveness of farmer response to changing conditions is enhanced by improved human capital of farmers (Schultz, 1975). Thus, improved rural schooling, additional farmer training and extension, better communication networks, and similar measures may be climate change policies in disguise since they are likely to improve farmers' ability to adapt to and possibly even mitigate climate change.

Business as usual among the world's poor is not adequate

Many of the world's poor still live in unacceptably desperate circumstances, and climate change is likely to add further burdens. Food prices are likely to increase. The livelihoods of poor farmers cultivating marginal land will be directly threatened. Besides the traditional development agenda, development efforts must attend to climate issues. This includes attention to warming, precipitation changes and increased climate variability, as well as attention to market impacts driven by changes in climate and climate policy (World Bank, 2009, p. 12).

Existing technology options must be made more accessible without overlooking complementary capacity and investments

Climate change will almost surely make life even harder for the world's poorest and most vulnerable populations; we must avoid restricting their capacity to adapt by limiting their options. Technology options must become more available. Although controversial in some places, biotechnology-based technologies have spread rapidly where ever they have not been severely restricted by government policies or related constraints. They will gain in importance in the context of climate change. Countries that do not yet have biosafety regulations should put these into place. The international community must reach sensible agreement on issues pertaining to traceability and liability. Where biophysical or legal constraints impede access to technology, continued institutional innovation will be required to build and improve on existing models of international agricultural research (CGIAR) and technology cooperation (PIPRA, AATF, etc.). These efforts must also acknowledge the need for complementary investments in the capacity to effectively and sustainably use new technologies, which is often a more binding constraint than intellectual property or other legal constraints.

Adaptation and mitigation in agriculture will require local responses, but effective policy responses must reflect global impacts and interlinkages

Policy changes in one location will change incentives elsewhere in the global economic system. These policy-induced changes are particularly important for climate change mitigation. The so-called "indirect land use" impacts of biofuels-induced grain price increases provides a canonical example of such global interactions in the agricultural economy. If land conversion or other derived changes in input use are important contributors to GHG emissions, then the consequences of any technology or policy for global resource use in agriculture must be a central concern. Similarly, assessment of the impacts of new crop varieties and traits on climate change requires careful consideration of how producers respond to these new technologies by changing what they choose to grow and where. The biggest impact of introducing drought tolerant maize varieties, for example, may well be to change the spatial range over which maize is grown, which may reduce maize prices and disadvantage maize farmers. Furthermore, since maize cultivation is associated soil erosion in some regions, the adaptation benefits of drought tolerance may come with net increases in GHG emissions.

National and international policymakers must therefore incorporate global economic linkages in any consideration of the impacts of global climate change on agriculture. Given the right kind of technology or institutional conditions, agricultural adaptation to changes in average precipitation and temperature can occur at relatively local levels. Adaptation to increased weather variability and increased frequency of extreme events, on the other hand, requires more than local responses. Adapting to such changes demands improved global connections via international trade and other global linkages – as economists have long documented that trade can reduce local price variability and reduce the need for local storage and other coping measures (Johnson, 1975; Martin and Anderson, 2010).

Trade will play a critical role in both mitigation and adaptation, but will itself be shaped importantly by climate change

Climate change will affect the global pattern of comparative advantage and attempts to block the force of global markets would be costly and counterproductive (Nelson et al., 2009). Regions facing major new climate and market realities may respond with large adjustments, say to new crops, rather than make marginal adjustments in a futile attempt to compete in markets that have moved. Investing in and encouraging adoption of marginal new technologies may be doomed to failure, however, when major changes, maybe even out of agriculture, are inevitable. Climate change may entail an even more rapid shift in some regional populations out of farming than would otherwise occur and assistance will be required in making these adjustments. Shifts of regional comparative advantage and movement of people out of agriculture defines world history. Wealthy nations such as Norway or Japan can support a few million of their globally non-competitive farmers with subsidy transfers, but such an approach cannot be successful for hundreds of millions of small farmers in poor countries. Thus, when considering both adaptation and migration, global agricultural responses must be at the center of the analysis.

Some specific policy priorities

A. **Invest in public agricultural R&D in developed countries**. Increasing public agricultural R&D investments in rich countries is essential; it is the major global engine of agricultural productivity and long term lower food prices for the poor (World Bank, 2009, Ch. 2009, Chapter 3). To respond to the challenges of climate change, these R&D investments should target general improvements in agricultural productivity, resistance to more variable growing conditions, water use efficiency, and reduced fossil fuel usage.
B. **Rebuild and expand public agricultural research capacity in developing countries**. New crop and trait combinations, as well as improved soil and water management practices, will be required to meet demands for global food security while at the same time coping with or even mitigating climate change. Policymakers must fund and improve public agricultural research capacity devoted to poor countries, especially those facing severe climate change. The CGIAR system can continue to play a key role in this process and

can provide a model for non-agricultural technologies as well (Correa, 2009), but developing countries must also prioritize their own national agricultural research systems and ensure that these systems are functional. Investments must entail long-term commitments for infrastructure and human capital that are meaningful enough to attract and retain well-trained, cutting-edge scientists. This requires national agricultural research systems to provide stronger, more dynamic professional incentives for their own researchers. Multilateral and bilateral investments must target countries where these reforms and long-term commitments are feasible. These and other research demands, many of which are highlighted as technologies above, should determine research priorities, which should leverage agricultural research from developed countries and ensure complementarities. The important role for public sector R&D does not preclude a vital role for profit-driven private sector R&D in developing countries. Each has a distinct role, with the public sector focusing on technologies where property rights and profitable opportunities are limited. Of course, when governments themselves are not stable and institutions are in flux then neither farmers nor investors can rely on the sustained R&D investments required for significant payoffs. Too often these R&D investments are wasted because long term research programs are abandoned before fruition, and adoption is hampered by a lack of institutional trust. Although none of these policy suggestions is easy to implement in ill governed regions, recent improvements in governance and institutions in many poor countries provide some optimism for a policy future where more options are viable.

C. **Harness agricultural biotechnology as a potentially important option**. Agricultural biotechnology use and trade regulations must be sufficiently flexible that they do not discourage the transfer or adoption of locally important innovations. Policy options related to this flexibility may relate to the protection of IP, including continued work to negotiate appropriate humanitarian use exemptions and preferential treatment. While governments may be able to help make privately-owned technologies more widely available and accessible by modifying IP rules and taking advantage of the flexibilities provided by international agreements such as the TRIPS Agreement at the WTO, public–private partnerships and other institutional arrangements may be even more effective in some cases. Support for agricultural biotechnology as an important option in the coming decades of challenging adaptation in agriculture is growing, but there remains a "critical need to get beyond popular biases against the use of agricultural biotechnology and develop forward-looking regulatory frameworks based on scientific evidence" (Fedoroff et al., 2010a,b).

D. **Encourage complementarities between public and private agricultural research**. Policy should appreciate, leverage and create complementarities between agricultural R&D in rich and poor countries and between that emerging from the public and private sectors. Governments and international institutions can help foster the use of biotechnologies to aid in mitigation and adaptation. Industry and government R&D can play complementary roles. Purely private incentives will likely fail to generate enough or the right types of innovation to for climate solutions. Obstacles to greater applicability and use of agricultural technology by developing country producers need to be overcome without reducing incentives for continued innovation of new technologies. Representatives from both the private and public sectors must build and further develop the flurry of institutional innovations that aimed to improve developing country access to agricultural technologies in the recent decade. The momentum behind creative remedies to potential IP problems in technology transfer provides a useful point of departure, but IP issues should also be kept in the proper perspective: in practice other constraints are often far more binding than IP.

E. **Help to mitigate risk**. Risk mitigation may involve a variety of private and government policy and institutions. While government supported crop insurance in developed countries has often been highly subsidized with little ability to sustain without substantial taxpayer support, ongoing research suggests that better designed insurance products may remedy some of these problems. There is evidence in India, for example, that farmers may be willing to purchase weather index insurance products even when these products are not subsidized.

F. **Invest in better information and forecasts**. Continued investments in remote sensing and weather forecasting are as important as ever. Improvements in sensing and communication technology and in modeling techniques have brought sophisticated short-term forecasts to many parts of the world. More must be done to improve longer-term seasonal forecasts and to develop more effective forecasts of slow onset events such as drought. Policies to support the diffusion of this information and to help interpret these forecasts in terms of their agronomic and economic implications are required to help both suppliers and demanders respond well to new information.

G. **Support competitive and responsive agricultural markets**. Policies and institutions that encourage the development of competitive and responsive input and output markets in agriculture should take on added urgency in the face of climate change. Appropriate responses to new climate conditions or even seasonal weather forecasts require the ability to make efficient production adjustments in response to these changing conditions. The single best gauge of efficiency when making these adjustments is provided by price signals in functional markets. Market rigidities from government price policies, parastatal restrictions, and dominant buyers (which may be local cooperatives) all limit the ability of farmers and others to adapt and adjust to disequilibria in a more dynamic and variable world.

H. **Encourage investments that improve spatial market integration**. Poorly integrated markets arising from inadequate communication and transportation infrastructure or other factors that create spatial frictions impede the transmission of price signals to rural producers and limit their ability to respond efficiently. As above, these market frictions will hamper climate change adaptation in agriculture and in agri-food markets more generally. Improvements in communications will no doubt continue without dedicated policy responses to climate change. Cell phones, for example, have penetrated most corners of the world and, in the process, have improved the spatial market integration of agricultural markets (e.g., Jensen, 2007). Rigidities introduced by weak transportation infrastructure and outdated government policies will, however, only be remedied with concerted policy efforts.

I. **Improve the measurement of agricultural GHG emissions**. It may be possible to refine GHG markets that stimulate innovation and adoption of agricultural technologies and practices that reduce global GHG emission. However, in order to harness carbon markets in this way, several challenges must first be met – many of which require a policy response. One immense challenge involves constructing effective metrics for GHG credits in agriculture. Creating these metrics will require institutional innovation and creative work to better understand and collect the necessary technological and economic information needed to measure GHG emissions in agriculture. Recognition of the importance off-site impacts of changes in farm practices increases the complexity of measurement, reporting and verification of GHG impacts. For example, unless global impacts including land use response is included in the calculations, metrics developed on a local or regional basis may make the climate situation worse not better.

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