Agricultural Technologies for Climate Change Mitigation and Adaptation in Developing Countries: *Policy Options for Innovation and Technology Diffusion*

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By Travis Lybbert and Daniel Sumner,
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CONTENTS

FOREWORD

> *"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, in particular, must become more available."*

Climate Change exacerbates the already daunting challenges facing the agricultural sector, and this is particularly the case in developing countries. Innovations in agriculture have always been important and will be even more vital in the context of climate change. The ICTSD-IPC Platform on Climate Change, Agriculture and Trade is pleased to present this thoughtful discussion about the need for effective policy responses to encourage the development, transfer and diffusion of appropriate agricultural technologies to promote food security, agricultural development and climate change adaptation and mitigation.

This paper by Dan Sumner and Travis Lybbert highlights technological and institutional innovations required to meet these challenges, the constraints to their development, transfer and dissemination and importantly suggests ways to overcome such constraints. Although there are no panaceas or silver bullets, the solutions are certainly not beyond our grasp. Indeed, policy recommendations on technology transfer to facilitate climate change adaptation and mitigation largely mirror those proposed as effective ways of promoting agricultural development. In this sense, climate change perhaps presents us with an opportunity: it reinforces the need to make greater progress on the transfer and dissemination of existing knowledge and technologies and to speed up the development and transfer of new innovations.

Ricardo Meléndez-Ortiz
Chief Executive, ICTSD

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EXECUTIVE SUMMARY

Climate has obvious and direct effects on agricultural production. Greenhouse gas (GHG) implications of agriculture are also obvious and large. The Intergovernmental Panel on Climate Change (IPCC) has reported that agriculture is responsible for over a quarter of total global greenhouse gas emissions. Given that agriculture's share in global gross domestic product (GDP) is about 4 percent, these figures suggest that agriculture is highly GHG intensive. This paper describes the potential role innovative agricultural practices and technologies can play in climate change mitigation and adaptation and aims to address the question: what policy and institutional changes are needed to encourage the innovation and diffusion of these practices and technologies to developing countries? We focus on developing countries in general with some specific references to Africa.

Concerns about mitigating and adapting to climate change are renewing the impetus for investments in agricultural research and are emerging as additional innovation priorities. In the coming decades, 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. 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. We describe some technologies that seem particularly promising in mitigating or adapting to climate change and use these 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. While new traits, varieti es and crops will play an important role, the range of relevant practice and technologies is much broader than this, including water management, production practices, post-harvest technologies, information and forecasting, and insurance.

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. In this context, institutions and policies are important at multiple scales. Impediments to the development, diffusion and use of relevant technologies can surface at several levels – from the inception and innovation stages to the transfer of technologies and the access to agricultural innovations by vulnerable smallholders in developing countries.

Potential constraints to innovation involve both the private and public sectors in both developing and developed countries. While the Consultative Group for International Agricultural Research (CGIAR) has been invaluable to developing countries as a source of agricultural innovation for nearly 40 years, many countries have a long history of large, direct government intervention in both input and output markets in agriculture that have stifled the formation of vibrant private firms and accompanying incentives to innovate.

The process of transferring agricultural innovations across agro-ecological and climatic zones is often subject to agronomic constraints. Agricultural biotechnology has relaxed some of these agronomic constraints, but it raises a new set of potential impediments in the form of biotechnology regulations. Although intellectual property (IP) can also constrain technology transfer, it is almost never the most important barrier. Where IP seems to pose a problem, recent institutional and legal innovations provide a point of departure for effective remedies.

Often, the most binding constraints occur at the adoption stage, with several factors potentially impeding poor farmers' access to and use of new technologies. These include static, poorly functioning or poorly integrated input or output markets; weak local institutions and infrastructure; inadequate or ineffective extension systems; missing credit and insurance markets.

From these considerations, we derive six policy principles. (1) The best policy and institutional responses will enhance information flows, incentives and flexibility. (2) Policies and institutions that promote economic development and reduce poverty will often improve agricultural adaptation and may also pave the way for more effective climate change mitigation through agriculture. (3) Business as usual among the world's poor is not adequate. (4) Existing technology options must be made more available and accessible without overlooking complementary capacity and investments. (5) Adaptation and mitigation in agriculture will require local responses, but effective policy responses must also reflect global impacts and inter-linkages. (6) Trade will play a critical role in both mitigation and adaptation, but will itself be shaped importantly by climate change.

These principles lead to several specific investments and policy priorities: (a) investing in public agricultural R&D in developed countries, (b) rebuilding and expanding public agricultural research capacity in developing countries, (c) harnessing agricultural biotechnology as a potentially important option, (d) encouraging complementarities between public and private agricultural research, helping to mitigate risk, (e) investing in better information and forecasts, (f) supporting competitive & responsive agricultural markets, and (g) encouraging investments that improve spatial market integration.

1. INTRODUCTION

Climate has obvious and direct effects on agricultural production. The effects of agriculture on GHG emissions are also large. Agriculture is a major part of the global economy and uses substantial fossil fuel for farm inputs and equipment. Animal agriculture also releases substantial GHGs in the form of nitrogen and methane. Furthermore, and probably more importantly, land clearing and preparation releases carbon from the living biomass that is removed from the land. The 2010 World Development Report draws on analysis of the Intergovernmental Panel on Climate Change (IPCC, 2007) to calculate that agriculture directly accounts for 14 percent of global GHG emissions in CO2 equivalents and indirectly accounts for an additional 17 percent of emissions when land use and conversion for crops and pasture are included in the calculations (World Bank, 2009).[1] Given that agriculture's share in global GDP is about 4 percent, these figures suggest that agriculture is highly GHG intensive.

The climate implications of agricultural production and practices have broadened the agricultural agenda over recent years to include responses to climate issues, and the climate change agenda has similarly subsumed agricultural production as both a contributor to climate change and, through adjustment in practices, a potential mitigating force. This paper describes the potential role innovative agricultural practices and technologies can play in climate change mitigation and adaptation and aims to address the question: What policy and institutional changes are needed to encourage the innovation and diffusion of these practices and technologies to developing countries? Our focus throughout is on developing countries in general, but we draw on specific features and examples from Africa to highlight the importance of this question and answers to it.

Organized 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. More recently, reducing the negative environmental spillover effects of agriculture has joined improving crop yields and other simple productivity indicators as a research pursuit. With a growing global population, with especially rapid population growth in some of the poorest places, with improved diets for the poor an imperative, and with evident local environmental impacts, agricultural innovation has never been more important. Climate issues add to this already challenging agenda.

Concerns about mitigating and adapting to climate change are now renewing the impetus for investments in agricultural research and are emerging as additional innovation priorities. In the coming decades, the development and effective diffusion of new agricultural 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. In this context, institutions and policies are important at multiple scales. Impediments to the development, diffusion and use of relevant technologies can surface at several levels – from the inception and innovation stages to the transfer of technologies and the access to agricultural innovations by vulnerable smallholders in developing countries. For example, cutting-edge agricultural technologies often emerge from developed countries. Thus, the institutional research capacity, human capital stock, innovation incentives and policies of

1 Such accounting is difficult in part because assigning activities to a particular part of the economy is often arbitrary. For example, is trucking materials to and from or even within the farm considered agriculture or transportation and is fertilizer processing considered agriculture or manufacturing?

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 agro-ecological 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, IP 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.

This paper begins with a brief background on the relationship between agriculture and climate change. In Section 3, the paper describes several technologies that may be useful to climate change adaptation and mitigation in developing countries. Keeping in mind these technologies – which are intended to be an illustrative rather than comprehensive set – Section 4 explores a variety of important considerations to their development, transfer and use. These considerations, which include both constraints and potential remedies, set the stage for our discussion in Section 5 of policy principles and priorities that could facilitate climate change mitigation and adaptation in poor countries by improving the innovation and diffusion of important agricultural technologies. The final section summarizes the paper and frames the discussion in a broader context of economic development in an era of greater complexity and greater urgency due to climate change.

2. BACKGROUND: CLIMATE CHANGE & AGRICULTURE

Forecasting climate change is imperfect, complex, important, and often controversial. While disputes remain, the consensus foresees accelerating increases in average annual temperature and changes in precipitation coupled with increasingly erratic intra-annual weather patterns. Stemming from these two primary dimensions of climate change (higher averages and more volatility) are melting glaciers and ice caps, rising sea levels and more frequent and more severe extreme weather events. Some of these changes will likely be shared globally – most places will get hotter – but other changes will vary geographically. For agriculturally important agro-ecological zones, higher level forecasting of daily weather extremes (frosts, the intensity and form of precipitation, extreme temperature, etc.) is crucial but even more demanding.

> ***More generally, developing countries are vulnerable to climate change because they depend heavily on agriculture, they tend to be relatively warm already, they lack infrastructure to respond well to increased variability, and they lack capital to invest in innovative adaptations.***

Despite these complex spatial differences in climate change, forecasts agree that many developing country climates will become less suitable for the agricultural practices they now undertake because places that now tend to be warm and humid will be disadvantaged relative to places that are now cooler (typically in the North). More generally, developing countries are vulnerable to climate change because they depend heavily on agriculture, they tend to be relatively warm already, they lack infrastructure to respond well to increased variability, and they lack capital to invest in innovative adaptations. Whereas the Stern report (Stern, 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) focuses on developing countries and estimates that without offsetting innovations, climate change will ultimately cause a decrease in annual GDP of 4% in Africa and 5% in India. At current growth rates, reductions of this magnitude would essentially offset GDP gains due to growth. Moreover, within these already poor regions, the largest effects will be on the poor who tend to earn their livelihoods in farming.

Estimating how climate change will affect agriculture adds complexity and uncertainty to already complex climate change models.[2] Amidst this complexity and imprecision, a fairly consistent pattern of direct agricultural impacts emerges: agriculture in temperate North America, Europe and Asia is likely to benefit from higher mean temperatures and longer growing seasons, while agriculture in much of the rest of the world will likely suffer declines in productivity. Higher temperatures in already-hot regions will likely reduce crop yields and effectively shorten the growing season by introducing (longer) periods of excessive heat. The best estimates currently available, which combine forecasts from the agronomic and limited economic modeling approaches, suggest that the aggregate impact of these effects will reduce global agricultural production by 6% by 2080 from what would otherwise occur.

To understand the economic impact of this reduction in agricultural productivity, one must consider other predictable ways in which 2080 will be different than today, namely: population growth (which will remain positive at least until 2050, but continue to slow in coming decades); income growth (which combined with population growth will expand food demand); and productivity gains in agriculture (which will continue to increase yields even with climate change). Thanks to these technology gains, global agricultural production is expected to increase substantially, albeit less than if climate change could have been avoided. The impact of climate change on food markets net of these other effects is more ambiguous, however, because food demand is expected to continue to expand with population and income growth. Overall, in 2080 we will likely produce more food than we currently do, but food may well be more expensive in real terms. This seemingly benign global snapshot is vastly incomplete, however, because it conceals dramatic regional and distributional impacts of these changes.

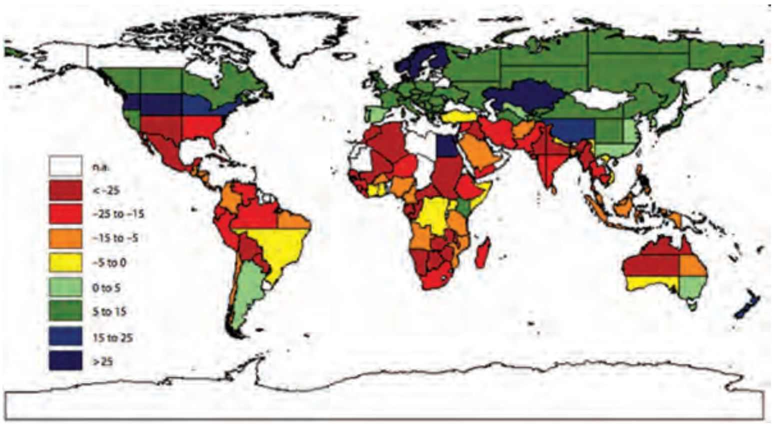
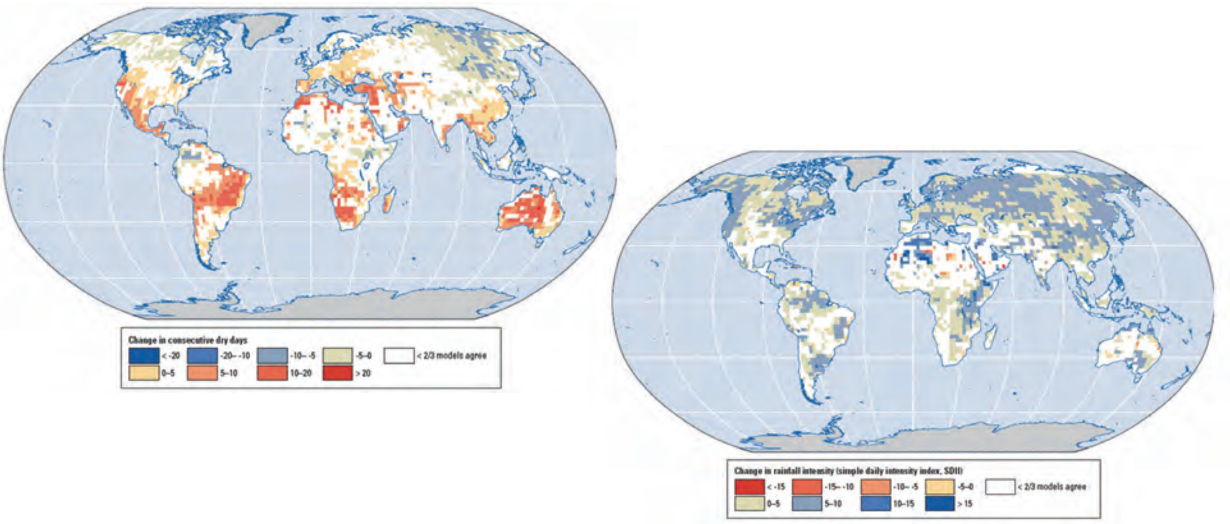


Figure 1. Projected impact of climate change on 2080 agricultural production assuming a 15% carbon fertilization benefit (SOURCE: Cline 2007).

2 Part of this added complexity is due to the agronomic responses to anticipated changes in average temperatures and precipitation. The agronomic impacts associated with more volatile weather patterns are even tougher to capture and add to the uncertainty. Much of the remaining complexity is due to the economic and technological responses to climate change: whereas climate is a natural system (albeit potentially influenced by humans), agriculture is a human activity that constantly changes in response to changing conditions. Thus, while agronomic models assess the impact of changes on crop yields and may explicitly define the scope of feasible technical adjustments producers make in response to these changes, the net effect depends at least as much on how producers respond to changing constraints and market incentives induced by these changes. Changes in the economic landscape follow from the fact that climate change affects global supplies and demands that in turn affect local market conditions and hence drive actual behavior of producers and consumers. Economic models include the impact of climate change across regions on relative prices and the value of agricultural production Kurukulasuriya, P., R. Mendelsohn, R. Hassan, J. Benhin, T. Deressa, M. Diop, H. Eid, K. Fosu, G. Gbetibouo, and S. Jain. 2006. «Will African Agriculture Survive Climate Change?» The World Bank Economic Review 20(3):367.. Economic models therefore account for adjustments suppliers and demanders make in response to changes in market incentives as well as local climate.

Regional disparities around the global average impact are substantial. India and Africa are projected to see reductions of agricultural output by 30% or more (Cline, 2007). Figure 1 summarizes the composite estimates compiled by Cline (2007) and shows how variable this impact is, with developing countries particularly hard hit. Such results focus on production potential and do not fully incorporate the increases in commodity prices that would accompany the reduction in production potential (relative to projected gradual declines that would occur without climate change). Higher commodity prices usually mean that farmers gain because demand for food and other farm output is price inelastic so that quantity demanded falls little when price rises, which implies that farm revenue is higher when output is lower. There are, however, important nuances to this observation. First, most poor farmers in poor countries have limited productive resources and are consequently net buyers of food. Higher real food prices hurt most poor farmers as a result. Second, farmers in less favored regions who continue to produce traditional crops that subsequently compete in global markets would lose out to farmers in more favored regions. The number of farms in developing countries is expected to decline by 2080 even without climate change as a function of general economic development, but with climate change this transition will happen even faster as many marginal areas in Africa and India may be forced to abandon agriculture altogether. The political tensions and urban pressures associated with this transformation could be particularly problematic.

There are many caveats associated with the forecasts for developing country agriculture displayed in Figure 1. Some see these forecasts as overly pessimistic because the models allow for only limited adaptation. Others see these models as overly optimistic because the models focus on the impact of changing averages rather than increasing weather volatility, which will also likely hit developing countries hardest in the form of extreme droughts, excessive rainfall and heat, and severe hurricanes. Two dimensions of higher variability (among many) – the forecasted changes in length of dry periods and rainfall intensity – are shown in Figure 2 (World Bank, 2009). While explicitly incorporating the effects of multidimensional volatility changes into agricultural impact forecasts is extremely difficult, these dramatic effects may well be the most important for local agricultural impacts and for thinking about policy and institutional responses. These policy and institutional responses will critically shape the impacts on developing countries in the coming decades.



Source: The World Climate Research Program CMIP3 Multi-model Database (https://esg.llnl.gov:8443/). Analysis by the World Bank.

Note: The maps show the median change (based on 8 climate models using SRES A1B) in annual values between 2030 and 2049, compared with 1980-1999. A "dry" day is defined as one with precipitation less than 1 millimeter whereas a "rainy" day has more than 1 millimeter. Precipitation intensity (SDII, or simple daily intensity index) is the total projected annual precipitation divided by the number of "rainy" days. White areas show areas of high model disagreement (fewer than two-thirds of the models agree on the sign of change).

Figure 2. Projected changes in length of dry periods (top) and rainfall intensity (bottom) (SOURCE: World Bank, 2009).

Almost certainly, climate change will be severe in most developing countries and will directly – and, in some cases, dramatically – hurt agricultural production in these countries. Moreover, the mix of adopted policies and institutions may play an even greater role determining the winners and losers from climate change. Over the decades required for climate change to occur, we can reasonably hope that most countries will see strong improvements in living standards. Yet, development cannot be taken for granted and the dual burden of climate change adaptation and mitigation may make economic transformation more difficult. These realities suggest an even more important role for appropriate agricultural policies and institution.

3. AGRICULTURAL TECHNOLOGIES FOR CLIMATE CHANGE MITIGATION & ADAPTATION

The core challenge of climate change adaptation and mitigation in agriculture is to produce (i) more food, (ii) more efficiently, (iii) under more volatile production conditions, and (iv) with net reductions in GHG emissions from food production and marketing. As long as climate change and 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 or force producers to recognize GHG emissions as an important and costly "input" in production processes and open 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.

The core challenge of climate change adaptation and mitigation in agriculture is to produce (i) more food, (ii) more efficiently, (iii) under more volatile production conditions, and (iv) with net reductions in GHG emissions from food production and marketing.

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. In this section, we describe some of these technologies in order to discuss policy and institutional considerations in the subsequent section. Some of these technologies have straightforward connections to climate change, but for others these connections are more nuanced. It is a fool's errand to attempt to fully catalog in any comprehensive way agricultural technologies with potential for climate change mitigation and adaptation over the next seven decades. If history is any guide, the most important such technologies have yet to be developed or even conceived. Hence, our objective is to highlight some specific relevant technologies or categories and to use these 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 & 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 (see Figure 3). The greatest latent productivity potential therefore resides in developing countries generally and in Sub-Saharan Africa in particular. 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, including deforestation and conversion to agricultural production account for 17% of global CO-2 emissions (World Bank, 2009), 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.

Since land use changes, including deforestation and conversion to agricultural production account for 17% of global CO-2 emissions productivity gains represent a significant mitigation mechanism in agriculture.

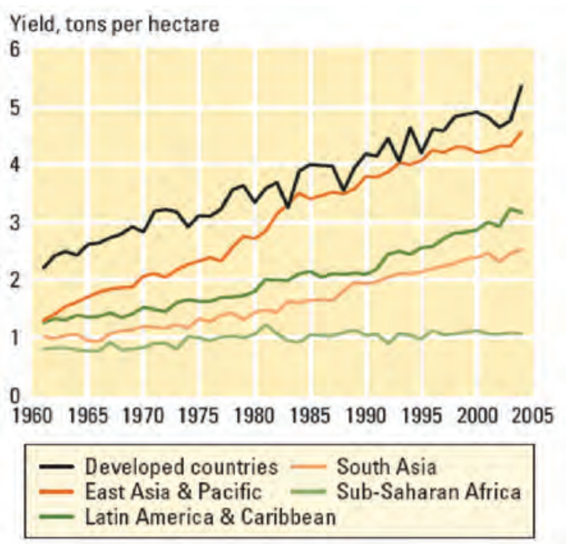


Figure 3. Average cereal yield by region (Source: WDR 2009).

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. 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.

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In many places, new traits and varieties for the crops farmers have traditionally cultivated will confer sufficient scope for adaptation. In other places, shifting to a totally different mix of crops will be required to cope with dramatic changes in rainfall or temperature, and cropping systems will fundamentally change as a result. Even if adaptation does not imply an entirely new mix of crops, many producers will benefit from new crops and varieties as they diversify their production portfolios as a means of stabilizing their revenue or local production of basic foods in the face of more volatile conditions. These diversification benefits will be important because many households and many regions will continue to produce their own food even decades from now, when transportation, communication and financial infrastructure has penetrated many areas that are currently poor and remote.

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 reduce the need for pesticides, they also reduce carbon emissions by decreasing pesticide demand as well as the number of in-field applications. Since a substantial proportion of the GHGs produced by agriculture are attributable to the production and application of nitrogen fertilizer alone (Stern, 2006), breakthroughs in nitrogen use efficiency could substantially mitigate emissions in agriculture.

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 reduce the need for pesticides, they also reduce carbon emissions by decreasing pesticide demand as well as the number of in-field applications. Since a substantial proportion of the GHGs produced by agriculture are attributable to the production and application of nitrogen fertilizer alone (Stern, 2006), breakthroughs in nitrogen use efficiency could substantially mitigate emissions in agriculture.

The mitigation potential of new crops and varieties extends to direct carbon sequestration and perhaps to second generation biofuel crops. There are several second generation biofuel crops (i.e., beyond sugar cane and maize) that appear promising as fuel sources (e.g., miscanthus, a focus of Mendel Biotechnology). These and others yet to be discovered likely require complementary innovation, for example, in cellulosic ethanol production. However, it is not clear whether these crops can compete successfully with farm, forest and urban waste products as bioenergy feed stock. And, of course, to the extent demand for biofuel feedstock draws on agricultural resources, such as land and water, it may drive up prices of food crops and tend to create additional resource pressures, especially for additional land use. Without compensating yield increases, shifting agricultural resources from food to fuel production intensifies challenges facing poor consumers already under stress from climate-induced declines in food productivity. Similar competition with food production could also emerge from active aforestation efforts that permanently take agricultural land out of production. While such aggregate tradeoffs between food production and other land uses are unlikely to create widespread long-run food shortages because they are governed by market and political pressures, they generate serious distributional concerns since higher food prices and local land use conflicts tend to predominantly harm the poor. In this fray of competing land uses, more productive traits, varieties and crops will soften the blow to these vulnerable sub-populations.

For the development of traits and varieties that help to mitigate and adapt to climate change, agricultural biotechnology stands out as an especially promising set of tools. While it remains 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. Many of the promising traits and varieties discussed above owe their existence to biotechnology, in-

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cluding genetically modified crops with pest resistance (Bt) and herbicide tolerance (Roundup Ready) 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 and other partnerships between public research institutes and private agricultural biotechnology firms such as Monsanto.

Water Efficient Maize for Africa (WEMA) Project

"In March 2008, Monsanto announced a public-private partnership to develop drought-tolerant maize varieties for Africa. The partnership, Water Efficient Maize for Africa (WEMA), links Monsanto with the African Agricultural Technology Foundation (AATF), the International Maize and Wheat Improvement Center (CIMMYT) and research systems in Kenya, South Africa, Tanzania, Mozambique and Uganda. The Bill & Melinda Gates Foundation and the Howard G. Buffett Foundation are contributing $47 million to fund the first five years of the project. WEMA aims to develop drought-tolerant African maize varieties—using conventional breeding, marker-assisted breeding and biotechnology. The goal is to eventually offer the drought-tolerance trait to small farmers in sub-Saharan Africa, royalty-free, so they are able to produce more reliable harvests. During moderate drought, the new varieties are expected to increase yields by 24-35 percent." (See http://www.monsanto.com/monsanto_today/2009/revisiting_wema.asp)

Genetically modified crops have benefited agriculture in many ways and in many locales – and they have simultaneously reduced GHG emissions by reducing demand for cultivated land and fossil fuel-based inputs. These reductions are most direct in the case of Bacillus thuringiensis (Bt) crops, which require fewer pesticide sprays. Although less direct, herbicide tolerance can also reduce emissions by enabling farmers to more readily adopt reduced- or no-till systems. These 'conservation agriculture' techniques (discussed in greater detail below) save fuel by reducing the need to plow and add carbon to the soil and thereby sequester carbon.

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 CO2 – the equivalent of removing over 6 million cars from circulation (Brookes and Barfoot, 2009).

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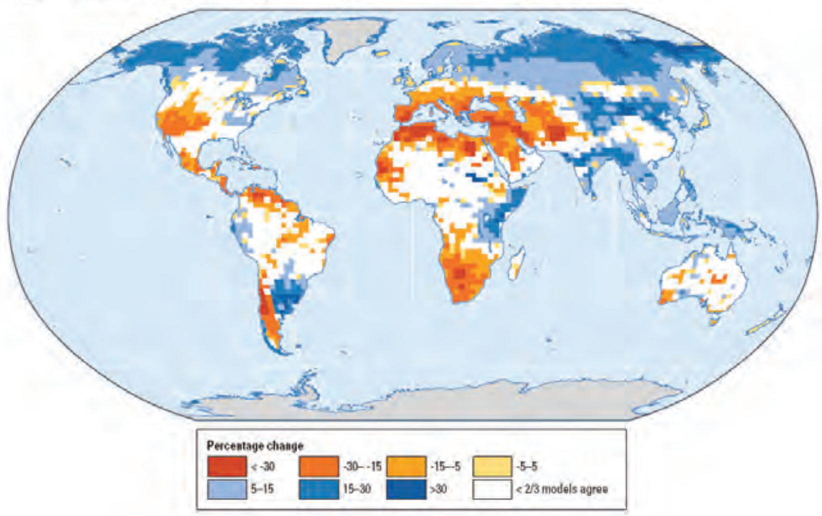
Water Management & Irrigation

In the midst of increasing urban and environmental demands on water, agriculture must improve water use efficiency generally. Adding climate change to this mix only intensifies the demands on water use in agriculture. 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 Stat, 2007), 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 could be the case that in some

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.

Map 3.1 Water availability is projected to change dramatically by the middle of the 21st century in many parts of the world.



Source: Milly and others 2008; Milly Dunne, and Vecchia 2005.

Note: The colors note percentage changes in annual runoff values (based on the median of 12 global climate models using the IPCC SRES A1B scenario) from 2041 to 2060 compared with 1900 to 1970. The white denotes areas where less than two-thirds of the models agree on whether runoff will increase or decrease. Runoff is equal to precipitation minus evaporation, but the values shown here are annual averages, which could mask seasonal variability in precipitation such as an increase in both floods and droughts.

Figure 4. Change in water availability by mid-21st Century (SOURCE: World Bank, 2009)

marginal areas, agricultural land use will cease and populations will migrate permanently.

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 (see Figures 2 and 4). 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).

> *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.*

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 (see Figure 2). In addition, where agriculture relies on snow pack for early season storage,

> *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.*

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 & Practices

Production techniques may be as important as production technologies in climate change adaptation and mitigation. One such technique stands out in particular: conservation or reduced tillage agriculture. 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. 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. The key challenge is to assure that such practices do not reduce yields so that the demand for additional land offsets the benefits from on-field sequestration.

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Marketing & Supply Chains

Whereas this paper considers mainly farm practices and technologies, the potential for GHG mitigation after products leave the farm is also crucial. It is well known that transportation is a major contributor of GHG emissions. Post harvest GHG emissions per unit of consumption mainly depend on efficiencies of transport (rail versus road, ocean shipping versus land shipping, and large loads versus small loads) 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

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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.

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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, inter-temporal 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 SMS 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., 2009).

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Insurance

Innovations in microfinance generally and in micro-insurance products specifically may aid farmers' capacity to adapt to climate change. This is especially true in production settings that are exposed to greater variability and more frequent extreme events (see Figure 2). Although microfinance has seen widespread success as a development intervention, many poor farmers continue to lack low-cost access to financial services such as savings and credit.

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

In the absence of these services, farmers often face serious constraints in their responses to both good and bad harvests and in their ability to adopt new technologies. The microfinance movement has significant momentum and will likely continue spreading into poor rural areas. The dramatic expansion of mobile phone networks into rural areas of developing countries and the emergence of SMS-based banking services will only speed farmers' integration into financial markets.

Compared to microfinance, micro-insurance innovation and availability is much more limited – although potentially just as important (Barrett, et al., 2007). Yet, the history of crop insurance in developed countries is not encouraging in the sense that large government subsidies to farmers and insurance companies have been required to maintain widespread use of multi-peril (e.g., rainfall, hail, drought, pests, etc.) insurance (Glauber, 2004). Beginning in the late 1990s, the World Bank and others began to experiment with weather risk insurance products based on weather or other indices. The payout of these index insurance products is based on an index that correlates strongly with farmers' production outcomes and that is commonly constructed based on remote sensing data. Presently, there are index insurance pilots and products being launched in many developing countries. Although the impetus for these efforts has primarily come from the public sector development community, private banks and re-insurance firms are actively involved. India, for example, has a growing and dynamic private micro-insurance sector. The challenge is to develop a sustainable insurance system that does not require such a large subsidy that it acts to raise expected incomes rather than as insurance against downside variability.

Livestock Insurance Based on Satellite Data in Kenya

Pastoralists in East Africa have adapted their livelihood to a remarkably harsh setting, yet regional climate changes will likely create volatility in rainfall patterns that are extreme even by East African standards. The International Livestock Research Institute (ILRI) – part of the Consultative Group on International Agricultural Research (CGIAR) – with funding from USAID and collaboration with Cornell University, University of Wisconsin-Madison, and Syracuse University has developed an index-based livestock insurance contract to help vulnerable pastoralists to cope with severe drought losses. The index uses measures of greenness (NDVI) based on satellite imagery to proxy for rangeland (and, by extension, the herd and livestock mortality risk). Researchers have worked closely with insurance companies to ensure that the design of the NDVI index tracks livestock mortality experience as closely as possible, that herders understand how the insurance product works, and that the pricing, marketing and distribution of the product preserve value to the herders. During pilot testing, pastoralists were very interested in the insurance product. In January 2010, Equity Bank of Kenya formally launched the product with the backing of international re-insurers and without government subsidization. While the herders themselves are the target clientele of this product, there is substantial interest in the product among NGOs and humanitarian agencies. One of the biggest problems in famine response continues to be substantial response lags due to normal delays between the onset of famine and the receipt of donations. These parties hope to use NDVI 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. (For more details about the project see http://www.basis.wisc.edu/live/ilbi_summary.pdf)

These index insurance products rely on measured weather outcomes and thereby reduce several practical problems associated with traditional production outcome (e.g., yield, livestock mortality) insurance, including adverse selection and moral hazard problems and administration and monitoring costs (Dischel, 2002, Hess, et al., 2002). For example, in arid and semi-arid rainfed systems, a cumulative rainfall index or one based on weekly weights according to the importance of rainfall timing within a growing season (e.g., Stoppa and Hess, 2003) can be highly correlated with production outcomes and therefore offer substantial value to producers if yield variability is a substantial contributor to income variability. In arid pastoral settings, index insurance that protects against severe drought losses will soon be available to East African pastoralists and appears to be promising (Mude, et al., 2009).

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, two limitations are worth noting. First, getting these products to smallholders may be difficult and costly. Demand for insurance among isolated smallholders may be weak because farmers fail to understand the value of insurance or because the insurance is not adequately correlated (negatively) with the main sources of risk as for example when local prices are inversely correlated with yield, which serves as a natural hedge. 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 (Chaniarat, et al., 2008)– an important improvement given that delays in response time continue to be the most important impediment to effective food aid responses.

A second limitation is that weather index insurance products in their current form seem to be most effective in relatively simple production environments that are heavily driven by a single weather outcome. Productivity in arid and semi-arid settings are often driven almost entirely by rainfall, which makes them especially well suited for index insurance products. In more complex, diversified production settings, a much broader set of weather events matters 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.

4. INNOVATION & DIFFUSION CONSIDERATIONS FOR AGRICULTURAL TECHNOLOGIES

This section describes impediments to the innovation and diffusion of agricultural technologies 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. We structure our discussion of constraints and potential remedies according to the innovation and diffusion process. We begin by describing relevant *innovation considerations* related to the conception, development or modification for developing country contexts of new agricultural technologies to address climate change. We then address *transfer considerations*, including constraints that can impede the delivery of these technologies to farmers and recent work to overcome these impediments. We conclude the section with access and *use considerations* that determine whether and how farmers or sub-sets of farmers in poor countries actually benefit from these technologies in practice.

> ***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 countries that rely even more on public research in agriculture.***

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 U.S. public spending on agricultural R&D fell to 0.8 percent per year from about 2.2 percent 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 countries that rely even more on public research in agriculture. Since 1990, public investments in agricultural R&D grew faster in developing countries than in developed countries. Public agricultural R&D in developing countries is now about half the world total compared to about 40 percent three decades ago (Alston et al. 2009). However, 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. Promising efforts to develop local R&D capacities in the past have been squandered by a lack of continuity and sustained investment. Moreover, limited local capacity has limited the ability to adapt new traits and varieties to local conditions. Private R&D has grown in importance, but remains mostly in developed countries. Indeed, 95 percent of private sector agricultural R&D is performed in developed countries. In developed countries private sector agricultural R&D has grown more rapidly than that in the public sector and, in the United States, for example, the private sector now accounts for more than half of all agricultural R&D (Alston et al. 2009).

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> ***Developing countries have often leaned heavily on the resources and research of the Consultative Group for International Agricultural Research (CGIAR), which was established in 1971 to continue and extend foundation-supported international agricultural R&D, in order to provide useful inputs to national systems in developing countries. 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.***

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Innovation constraints in many developing countries stem from deeper problems in the agricultural sector. Many of these countries have a long history of large, direct government intervention 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), but 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 responsive and dynamic 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, 2004, Masters, 2005), the diversity and complexity of agriculture may pose challenges to such remedies even if similar approaches are workable in the pharmaceutical industry: human physiology and responses to clinical treatments vary far less than do agro-ecological conditions and agronomic responses to growing conditions.

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Arguments for public funding of agricultural research have often hinged on the positive externalities associated with enhanced agricultural productivity. Similar arguments may soon be heard to support funneling public agricultural R&D funds toward climate change mitigation and adaptation. As long as carbon is not incorporated into pricing, however, there will be insufficient incentives for agricultural technologies that may mitigate climate change. Conversely, putting a price on carbon, may create incentives for research and innovation in agricultural technologies and practices (e.g., Kaonga and Coleman, 2008, Woelcke and Tennigkeit, 2009).

Creating functional carbon markets that can incorporate the full GHG impacts of agricultural practices or technologies is, however, 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. 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

Developing countries often rely heavily on agricultural research conducted internationally (e.g., within the CGIAR and by both the public and private sectors in rich countries) and therefore on the international transfer of new technologies and research tools. The process of transferring agricultural innovations across agro-ecological and climatic zones is often subject to agronomic constraints. The classic constraint of this sort stems from the fact that new varieties and crops must be suitable to the growing conditions of a particular locale before it can be successfully introduced. Here, the distinction between early or 'upstream' research stages 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.

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Agricultural biotechnology has revolutionized plant breeding in ways that relax some of these agronomic constraints. For example, 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.

There are natural spillovers between similar agro-ecological zones. Having the good fortune of sharing similar growing conditions with a country with cutting-edge research capacity and resources can therefore remedy many of these agronomic transfer constraints. In this respect, Africa suffers from a wide diversity of agro-ecological zones, which require substantial modification of promising varieties developed elsewhere (see Figure 5). The impact of this agro-ecological diver-

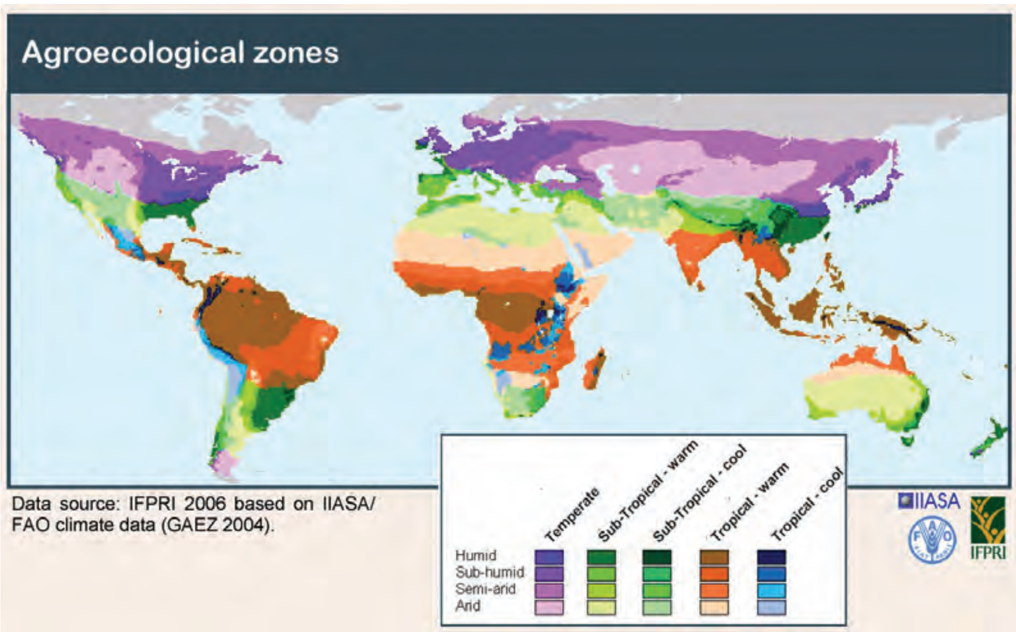

Figure 5. Agroecological zones that can complicate the transfer of agricultural technologies (see http://harvestchoice.org/production/biophysical/agroecology)

sity on technology diffusion and the returns to agricultural R&D have been carefully documented by researchers at IFPRI as part of the HarvestChoice program (Wood and Pardey, 1998).

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Non existing or overly restrictive GM crop regulations obviously constrain downstream research stages, including the release and diffusion of new traits and varieties, but so can intellectual property rights (see Blakeney, 2009 for a careful exposition of IP issues related to agriculture). 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".

Recently, some have drawn parallels between the patents and access to medicines debate 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 many of the same arguments and created similar battle lines and alliances as the essential medicines debate (see box). 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 dealing with patents.[4]

The UNFCCC Discussions on Technology Transfer & Intellectual Property Rights

Derived from discussions to "enable the full, effective and sustained implementation of the Convention through long-term cooperative action, now, up to and beyond 2012," the 2007 Bali Action Plan identified technology development and transfer as a priority area. Since then, intellectual property rights have emerged as a particularly controversial issue in climate change discussions relating to technology transfer.

On the one hand, a number of developing countries and non-governmental organizations (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. As a result, current references to intellectual property rights in the UNFCCC draft negotiation text are still under negotiation.

While the Copenhagen Accord mentions the establishment of a 'Technology Mechanism' to accelerate technology development and transfer, the role of intellectual property rights is not mentioned explicitly. Discussions on this issue are likely to continue until the United Nations Framework Convention meeting in Cancun in 2010 and beyond.

4 Although the compulsory licensing of essential medicines has increased since the Doha Declaration in 2001, it continues to be used only rarely and primarily as a bargaining chip in negotiations with patent holders rather than as a viable licensing strategy. In the case of agricultural technologies, compulsory licensing is rarer still. A number of countries (e.g., Canada, Japan and Brazil) were nonetheless careful to include provisions allowing compulsory licensing in their plant variety legislation. The potential use of compulsory licensing in this area, while surely limited, should not be disregarded outright.

The development of new varieties, particularly through agricultural biotechnology, often draws on several sources of more basic IP and adjudicating ownership or share in the returns from the final product is at the very least complex and in more extreme cases may eliminate the incentive to develop the applicable product at all.

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 (see box). The development of new varieties, particularly through agricultural biotechnology, often draws on several sources of more basic IP and adjudicating ownership or share in the returns from the final product is at the very least complex and in more extreme cases may eliminate the incentive to develop the applicable product at all. These so-called "patent thickets" can stymie innovation because the resulting "anticommons" with too many property rights holders can in theory introduce almost paralyzing frictions and produce inefficient outcomes (Heller and Eisenberg, 1998).

Golden Rice: The Catalyst for Intellectual Property & Licensing Innovations Aimed at Humanitarian Use Technology Transfer

Golden Rice was catapulted into the global spotlight in 2000 when it graced the cover of Time magazine along with its inventor Ingo Potrykus. It was heralded as a potential solution to the long standing problem of vitamin A deficiency and its damaging effects on eyesight, particularly among children and pregnant and lactating women. Through the application of biotechnology, Potrykus had devised a clever technique for shifting the production of beta-carotene, the precursor to vitamin A, in the rice plant from the foliage and other parts of the plant to the edible grain. Due to the timing of its arrival, Golden Rice was quickly harnessed in the potent confluence of debates about agricultural biotechnology and globalization.

In 2000, a detailed analysis of the intellectual property dimensions to the development of Golden Rice was published (Kryder, et al., 2000), which documented roughly 70 patents and patent applications that were implicated in the development of Golden Rice. 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 facilitated the negations 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).

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.

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', including the Public Intellectual Property Resource for Agriculture (PIPRA) and the African Agricultural Technology Foundation (AATF). (For a case study of Golden Rice and intellectual property negotiations, see http://www.iphandbook.org/handbook/case_studies/cs03/ .)

While these IP frictions are real, they are not insurmountable. Again, the Golden Rice case is insightful: it not only illustrated the potential problem in the case of agricultural technologies and the poor, but also catalyzed substantial efforts and investments to remedy the problem. A variety of remedies to this technology transfer constraint have emerged, including humanitarian use licensing (Lybbert, 2002), patent pools and public-private partnerships. While patent pools have a history among private firms (Lerner and Tirole, 2004), they 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. Still, 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). Two specific efforts to leverage such remedies in the case of agricultural technologies are worth highlighting here.

First, the Public Intellectual Property Resource for Agriculture (PIPRA) (Atkinson, et al., 2003) was conceived in the wake of efforts to understand the IP implications of Golden Rice (see box) 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. A look at some of PIPRA's services sheds light on specific and important transfer constraints: IP analysis and training, commercialization strategies, drafting and negotiating licensing agreements, and structuring public-private partnerships. In conjunction with the Center for the Management of Intellectual Property and Health Research and Development (MIHR), PIPRA published an 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/). The handbo ok includes case studies, sample licensing agreements, including those with humanitarian use terms, and detailed discussions that will be valuable to the management of IP aimed at improving the transfer of relevant agricultural technologies for climate change adaptation or mitigation.

The second public-private initiative that is particularly relevant is the African Agricultural Technology Foundation (AATF), which was similarly conceived in the wake of the Golden Rice case[5] as an institutional innovation to reduce frictions in the transfer of agricultural technologies to smallholder farmers in Africa. The AATF is a non-profit organization that "promotes public-private partnerships for the access and delivery of appropriate proprietary agricultural technologies for use by resource-poor smallholder farmers in Sub-Saharan Africa." (see http://www.aatf-africa.org). It offers "expertise and know-how that facilitates the identification, access, development, delivery and utilization of proprietary agricultural technologies" with the aim of reducing food security and poverty reduction in Sub-Saharan Africa. Among other things, it plays a primary coordinating role in the WEMA project described above.

Since IP issues typically figure prominently in discussions of technology transfer, we conclude this subsection by taking stock of implications for agricultural technologies to mitigate or adapt to climate change. It is important to recognize that for many of the agriculture technologies described above, IP issues play

5 Recognition of potential frictions in agricultural technology transfer related to intellectual property and their particular relevance to developing countries was building before the Golden Rice case. Given the high profile Golden Rice quickly assumed, however, it provided a powerful impetus to the donor community to take these potential constraints seriously and to support innovative efforts to offer remedies.

only a minor role. Where IP issues arise, they are at times complicated but not impenetrable. As a practical matter, many of the IP issues that are likely to arise with climate change mitigation and adaptation in developing countries are familiar. Consequently, some of the IP remedies discussed above are directly relevant to the transfer of future technologies related to climate change. Best practices related to humanitarian use licensing, for example, may reduce frictions in the transfer of technology to the rural poor in important ways. Initiatives such as PIPRA and AATF have created a meaningful space in which ongoing institutional innovation can occur.

How relevant might these institutional innovations be for facilitating the transfer of climate change technologies? In response to this question, it is important to note that these institutions have emerged in part because the complexity and diversity in agriculture (see Figure 5) 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 could blur in the coming decades. Many of these technologies may be less sensitive to agroecological conditions than traditional crop varieties can be. For example, with biotechnology, techniques may become increasingly easy to incorporate into local varieties, especially as capacity to use these techniques continues to spread. Notice this tradeoff: with less location-specificity, agroecological differences may matter less, but this implies less physical separation between profitable and humanitarian uses 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.

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 could blur in the coming decades.

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Finally, it is worth emphasizing that despite the conventional rhetoric, these IP related concerns involve much more than royalties. While the distance and differences between these 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 ad-

While the distance and differences between these 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 cooperation often hinges more on these stewardship concerns than on royalty concerns.

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Technology transfer constraints and concerns deserve continued attention: 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 & 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 stem from the same domestic roots that create 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.

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.

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 extension systems in some countries seriously limit the adoption 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. Missing credit and insurance markets can discourage the adoption of new technologies as well.

In a similar way, government management of agricultural output markets can stifle growers' ability or incentives to adopt new varieties and crops. Lack of direct incentives to adapt to new market conditions because market prices are not allowed to flow through to farmers, means that they often 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 inter-temporal benefits –

> *The adoption of some technologies and techniques – particularly those that confer stochastic or inter-temporal benefits – involves a complex learning process for farmers.*

involves a complex learning 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 streams such as this are notoriously difficult for breeders to assess and even tougher for poor farmers to evaluate given their relative lack of control over other production factors (Lybbert and Bell, 2009). 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 learn.

Access and use constraints often differ across farmers. Many of the above constraints are particularly severe for small farmers on land that lacks adaptation options. These farmers are also likely to be the most vulnerable to negative impacts of climate change. Small farmers often are typically less integrated in both input and output markets and lack access to financial markets and services. In some regions, these farmers are also subject to more unpredictable growing conditions, which can hamper their ability to assess the value of new technologies such as drought tolerance. Private seed companies, for example, are frequently unable to justify investing in research that targets small farmers operating on land with severe constraints. 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.

5. POLICY AND INSTITUTIONAL PRINCIPLES & PRIORITIES

The set of potentially relevant agricultural technologies is diverse. The survey of technologies in the prior section is indicative of this broad and diverse set, but it obviously misses a vast pool of yet undiscovered technologies that will be critically important to climate change adaptation and mitigation in agriculture. The development and diffusion of all these technologies hinge crucially on policies and institutions. 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. We begin by outlining several policy 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 Principles

1. The best policy and institutional responses will 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.

> *With changing climates and changing policy environments, information for better decision making is crucial for growers, upstream suppliers and downstream marketers.*

2. Policies and institutions that promote economic development and reduce poverty will often improve agricultural adaptation and may also pave the way for more effective climate change mitigation through agriculture. 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 have particular urgency going forward.

3. 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, which are so important for poor consumers, are likely to increase and the livelihoods of net food purchasing farmers will be directly threatened. Thus, besides the traditional agenda, development efforts must attend to climate issues. This includes attention to warming, precipitation and increased climate variability, as well as attention to market impacts driven by changes in climate and climate policy (World Bank, 2009). Likewise, climate change financing to support adaptation and mitigation in developing countries must prioritize the agricultural sector.

4. Existing technology options must be made more available and 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, in particular, must become more available. Although agricultural biotechnology remains controversial in some circles, biotechnology-based products have spread rapidly where they have not been severely restricted by government policies or related constraints and will gain in importance in the context of climate change. Countries that do not yet have biosafety regulations should put these into place, and 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.

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5. Adaptation and mitigation in agriculture will require local responses, but effective policy responses must also reflect global impacts and inter-linkages. We have outlined how the global climate system interacts with the global economy, implying that global responses must be considered for any policy or institutional change. A policy change in one location will change incentives elsewhere in the global economic system. These off-site responses to policy-induced changes in local behavior 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, but this is only an indicator of the general proposition. If land conversion or other derived changes in input use are important contributors to GHG emissions, then

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.

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 very well be to change the spatial range over which maize is grown.

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 will demand greater global interdependence via international trade and other global linkages.

6. 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 globally non-competitive farmers, 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). These R&D investments should target general improvements in agricultural productivity, resistance to more variable growing conditions, water use efficiency, and reduced input intensity.

b. **Rebuild and expand public agricultural research capacity in developing countries:** New crop and trait combinations 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 in 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. These priorities should also 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 part of the whole has a distinct role, with the public sector focusing on technologies where property rights and profitable opportunities are limited.

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., 2010).

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 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 aims 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 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 & 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 & 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 of 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.

6. CONCLUSION

As we consider implications of and responses to climate change, continuing concerns for improvements in nutrition, food security, food safety, local environments, and rural communities must not be neglected. Current poverty – and the hunger and other tragedies that it entails – demand immediate attention. Agricultural development efforts cannot be diverted even while recognizing the importance of climate change and the interaction between climate and other agricultural issues. Given the reliance of the poor on agriculture and the sensitivity of agriculture to climate change, impending climate changes will almost certainly hit (currently) developing countries and vulnerable populations within these countries hardest. While this reality seems to make the development process more complex, it should also stimulate greater urgency in addressing rural poverty and vulnerability. These twin imperatives of climate change – greater complexity and greater urgency – are important to keep in mind when formulating policies and institutions aimed at improving climate change adaptation and mitigation in agriculture. The technologies we have discussed, along with the many more that are yet to be discovered, can each make important contributions, but there are no quick, technological shortcuts. For example, biotechnology has an important role in dealing with several of these issues, but is not a quick and easy solution to addressing climate concerns and other agricultural development issues. Furthermore, its efficacy depends on the broader technological, economic, environmental, and political context.

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While the past half century has seen a mixed record of economic development across countries, there have been remarkable successes on every continent and the average human being today is substantially better off than his or her grandparents (thanks especially to impressive economic growth in both India and China). Over the next several decades – the same period we are expected to see dramatic climate changes – we can optimistically hope that many of today's rural poor in South Asia, Africa and other regions see dramatic economic improvements that will facilitate their capacity for climate change adaptation and mitigation. Even with these hoped for improvements, however, the sensitivity of agriculture to climate change remains a global concern.

Agriculture has a unique role in development. It is our primary source of food, has significant potential for mitigation of global GHG emissions, and is particularly sensitive to climate change. Innovations in agriculture have always been important and will be even more vital in the context of climate change. Thoughtful policy responses that encourage the development and diffusion of appropriate agricultural technologies will be crucial to enabling an effective technological response. A careful balance of institutional change and wise investments is required to deal with both the demands of climate change and the demands of improving lives of the poor.

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REFERENCES

Jones, J. W.; Hoogenboom, G.; Porter, C. H.; Boote, K. J.; Batchelor, W. D.; Hunt, L. A.; Wilkens, P. W.; Singh, U.; Gijsman, A. J. and Ritchie, J. T. "The Dssat Cropping System Model." *European Journal of Agronomy*, 2003, 18(3-4), pp. 235-65.

Alston, J.M., J.M. Beddow, and P.G. Pardey. 2009. "Agricultural Research, Productivity, and Food Prices in the Long Run." *Science* 325(5945):1209.

Atkinson, R., R. Beachy, G. Conway, F. Cordova, M. Fox, K. Holbrook, D. Klessig, R. McCormick, P. McPherson, and H. Rawlings III. 2003. "Intellectual Property Rights: Public Sector Collaboration for Agricultural Ip Management." *Science* 301(5630):174.

Barrett, C.B., B.J. Barnett, M.R. Carter, S. Chantarat, J.W. Hansen, A.G. Mude, D. Osgood, J.R. Skees, C.G. Turvey, and M.N. Ward. 2007. "Poverty Traps and Climate Risk: Limitations and Opportunities of Index-Based Risk Financing." *SSRN*.

Blakeney, M. 2009. *Intellectual Property Rights and Food Security*. Wallingford, Oxfordshire, UK ; Cambridge, MA: CABI.

Brookes, G., and P. Barfoot. "Gm Crops: Global Socio-Economic and Environmental Impacts 1996-2007." PG Economics Ltd, UK, May.

Chaniarat, S., C.G. Turvey, A.G. Mude, and C.B. Barrett. 2008. "Improving Humanitarian Response to Slow-Onset Disasters Using Famine-Indexed Weather Derivatives." *Agricultural Finance Review* 68.

Cline, W.R. 2007. *Global Warming and Agriculture : Impact Estimates by Country*. Washington, DC: Center for Global Development : Peterson Institute for International Economics.

Correa, C. "Fostering the Development and Diffusion of Technologies for Climate Change: Lessons from the Cgiar Model." International Centre for Trade and Sustainable Development, December.

Dischel, R.S. 2002. *Climate Risk and the Weather Market : Financial Risk Management with Weather Hedges*. London: Risk Books.

Fedoroff, N.V., D.S. Battisti, R.N. Beachy, P.J.M. Cooper, D.A. Fischhoff, C.N. Hodges, V.C. Knauf, D. Lobell, B.J. Mazur, D. Molden, M.P. Reynolds, P.C. Ronald, M.W. Rosegrant, P.A. Sanchez, A. Vonshak, and J.K. Zhu. 2010. "Radically Rethinking Agriculture for the 21st Century." *Science* 327(5967):833-834.

Glauber, J. 2004. "Crop Insurance Reconsidered." *American Journal of Agricultural Economics* 86(5):1179-1195.

Hallstrom, D.G., and D.A. Sumner (2000) Agricultural Economic Responses to Forecasted Variation: Crop Divesification, Storage and Trade. Palisades, New York, Instituted for Climate Prediction, pp. 285-261.

Heller, M.A., and R.S. Eisenberg. 1998. "Can Patents Deter Innovation? The Anticommons in Biomedical Research." *Science* 280(May 1):698-701.

Hess, U., K. Richter, and A. Stoopa (2002) Weather Risk Management for Agriculture and Agri-Business in Developing Countries, ed. R.S. Dischel. London, Risk Books, pp. xviii, 325.

ICTSD. "Technologies for Climate Change and Intellectual Property: Issues for Small Developing Countries." International Centre for Trade and Sustainable Development, October.

IPCC. 2007. *Climate Change 2007: Synthesis Report. Contributions of Working Groups I, Ii, and Iii to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva: IPCC.

Jensen, R. 2007. "The Digital Provide: Information (Technology), Market Performance, and Welfare in the South Indian Fisheries Sector*." *The Quarterly Journal of Economics* 122(3):879-924.

Kaonga, M.L., and K. Coleman. 2008. "Modelling Soil Organic Carbon Turnover in Improved Fallows in Eastern Zambia Using the Rothc-26.3 Model." *Forest Ecology and Management* 256(5):1160-1166.

Kryder, R., S. Kowalski, and A. Krattiger. 2000. "The Intellectual and Technical Property Components of Pro-Vitamin a Rice (Goldenrice™): A Preliminary Freedom-to-Operate Review'." *ISAAA Briefs* 20:74.

Kurukulasuriya, P., R. Mendelsohn, R. Hassan, J. Benhin, T. Deressa, M. Diop, H. Eid, K. Fosu, G. Gbetibouo, and S. Jain. 2006. "Will African Agriculture Survive Climate Change?" *The World Bank Economic Review* 20(3):367.

Lehmann, J., J. Gaunt, and M. Rondon. 2006. "Bio-Char Sequestration in Terrestrial Ecosystems–a Review." *Mitigation and adaptation strategies for global change* 11(2):395-419.

Lerner, J., and J. Tirole. 2004. "Efficient Patent Pools." *American Economic Review* 94(3):691-711.

Lybbert, T.J. 2002. "Technology Transfer for Humanitarian Use: Economic Issues and Market Segmentation Approaches." *Intellectual Property Strategy Today* 5:17-24.

Lybbert, T.J., and A. Bell. 2009. "Stochastic Benefit Streams, Learning and Technology Diffusion: Why Drought Tolerance Is Not the New Bt." *Working Paper* University of California, Davis.

Maskus, K. "Differentiated Intellectual Property Regimes for Environmental and Climate Technologies." OECD, 21 October 2009.

Masters, W.A. 2004. "Prizes for Innovation in African Agriculture: A Framework Document." Department of Agricultural Economics, Purdue University and Center on Globalization and Sustainable Development, The Earth Institute at Columbia University), 39 pp. Available at www. earth. columbia. edu/cgsd/prizes.

---. 2005. "Research Prizes: A New Kind of Incentive for Innovation in African Agriculture." *International journal of biotechnology* 7(1):195-211.

Mude, A., S. Chantarat, C.B. Barrett, M.R. Carter, M. Ikegami, and J. McPeak (2009) Insuring against Drought-Related Livestock Mortality: Piloting Index Based Livestock Insurance in Northern Kenya.

Mude, A.G., C.B. Barrett, J.G. McPeak, R. Kaitho, and P. Kristjanson. 2009. "Empirical Forecasting of Slow-Onset Disasters for Improved Emergency Response: An Application to Kenya's Arid North." *Food Policy* 34(4):329-339.

Schultz, T. 1975. "The Value of the Ability to Deal with Disequilibria." *Journal of Economic Literature*:827-846.

Stern, N.H. 2007. *The Economics of Climate Change : The Stern Review*. Cambridge, UK ; New York: Cambridge University Press.

Stoppa, A., and U. Hess (2003) Design and Use of Weather Derivatives in Agricultural Policies: The Case of Rainfall Index Insurance in Morocco. Capri, Italy.

Sumner, D., D. Hallstrom, and H. Lee. 1998. "Trade Policy and the Effects of Climate Forecasts on Agricultural Markets." *American Journal of Agricultural Economics* 80(5):1102-1108.

Woelcke, J., and T. Tennigkeit. 2009. "Harvesting Agricultural Carbon in Kenya." *Rural 21* 43(1):26-27.

Wood, S., and P.G. Pardey. 1998. "Agroecological Aspects of Evaluating Agricultural R&D." *Agricultural Systems* 57(1):13-41.

World Bank. "Development and Climate Change." World Bank.

About the Platform

In 2008 the International Food & Agricultural Trade Policy Council (IPC) and the International Centre for Trade and Sustainable Development (ICTSD) launched The ICTSD-IPC Platform on Climate Change, Agriculture and Trade. This interdisciplinary platform of climate change, agricultural and trade experts seeks to promote increased policy coherence to ensure effective climate change mitigation and adaptation, food security and a more open and equitable global food system. Publications include:

- International Climate Change Negotiations and Agriculture.
  Policy Brief No.1, May 2009

- Greenhouse Gas Reduction Policies and Agriculture: Implications for Production Incentives and International Trade Disciplines.
  Issue Brief No.1, by D. Blandford and T. Josling, August 2009

- Climate Change and Developing Country Agriculture: An Overview of Expected Impacts, Adaptation and Mitigation Challenges and Funding Requirements.
  Issue Brief No.2 by J. Keane, S. Page, A. Kergna, and J. Kennan, December 2009

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  Issue Brief No.6 by T. Lybbert and D. Sumner, May 2010

About the Organizations

The International Centre for Trade and Sustainable Development was established in Geneva in September 1996 to contribute to a better understanding of development and environment concerns in the context of international trade. As an independent non-profit and non-governmental organization, ICTSD engages a broad range of actors in ongoing dialogue about trade and sustainable development. With a wide network of governmental, non-governmental and inter-governmental partners, ICTSD plays a unique systemic role as a provider of original, non-partisan reporting and facilitation services at the intersection of international trade and sustainable development. More information is available at **www.ictsd.org**.

The International Food & Agricultural Trade Policy Council promotes a more open and equitable global food system by pursuing pragmatic trade and development policies in food and agriculture to meet the world's growing needs. IPC convenes influential policymakers, agribusiness executives, farm leaders, and academics from developed and developing countries to clarify complex issues, build consensus, and advocate policies to decision-makers. More information on the organization and its membership can be found on our website: **www.agritrade.org**.