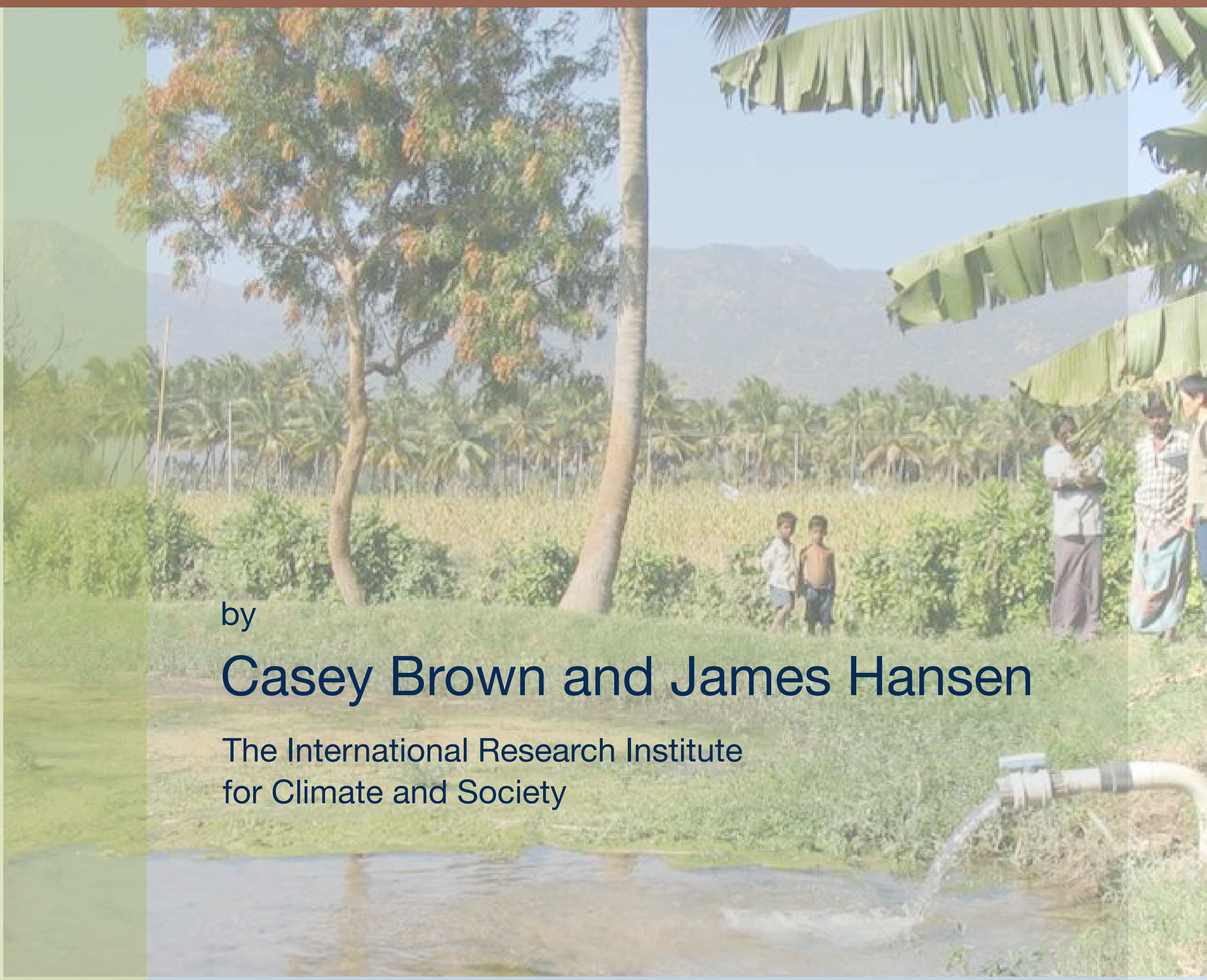
AGRICULTURAL WATER MANAGEMENT AND CLIMATE RISK



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Agricultural Water Management and Climate Risk

Report to the Bill and Melinda Gates Foundation

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International Research Institute for Climate and Society

April, 2008

Summary

Exposure to a high degree of climate risk is a characteristic feature of rainfed agriculture in the drylands of sub-Saharan Africa and parts of South Asia. A growing body of evidence links unmitigated hydroclimatic variability to poor economic growth in developing countries. At a more local level, climate exerts a profound influence on the lives of poor rural populations who depend on agriculture for livelihood and sustenance, who are unprotected against climate-related diseases, who lack secure access to water and food, and who are vulnerable to hydrometeorological hazard. Several mechanisms by which climate risk impacts rural households combine with other factors to trap rural populations in chronic poverty. Climate change is expected to intensify many of the challenges facing dryland agriculture in Africa and South Asia, but in ways that can only be partially anticipated.

Improved control of water resources is a fundamental method for mitigating the impacts of climate variability. Methods range from small scale on-farm and community based measures with local control to large scale infrastructure with institutionalized and governmental control. There are tradeoffs inherent in any selection of water management approaches at any scale. One commonly overlooked tradeoff is the relationship between scale and reliability, where reliability of water supply decreases as the scale of water management intervention decreases. African countries and parts of India lack public or private infrastructure to provide storage to mitigate the variability of rainfall. The investments in agricultural water management that are viable for dryland agriculture in Africa in the foreseeable future provide only partial control and leave substantial residual risk. The infeasibility of achieving a high level of water control across the vast dryland farming regions of Africa in the near to medium term, and increasing stress on groundwater and surface water resources in much of India point to the need to exploit every opportunity to deal with the residual climate risk that water control systems alone cannot mitigate.

We introduce the concept of residual risk to communicate the limitations of agricultural water management (or any singular approach) for managing climate risk and to facilitate the consideration of unmanaged climate risk. Managing that residual risk in dryland agriculture calls for several investments in parallel with improving agricultural water management. Opportunities include crop germplasm improvement, livelihood diversification, rural climate information systems, financial risk transfer and improved hazard early warning and response.

We propose three specific areas of investment that we consider timely and promising. Each targets a different layer of risk: (a) climate-informed investment in water management to increase the resilience of agricultural development and stimulate investment; (b) rural climate information services to support adaptive management of water and production activities, as a way to manage residual risk with incomplete water control; and (c) integrated, multi-hazard (drought-flood-food insecurity) early warning systems to support more timely and better coordinated response to climatic shocks that exceed the coping capacity of rural communities.

Contents

1. Climate, Water, Agriculture and Development

Exposure to a high degree of climate risk is a characteristic feature of rainfed agriculture in the drylands[i] of sub-Saharan Africa and parts of South Asia, which were largely bypassed by the Green Revolution, and where poverty and food insecurity remain most prevalent (Fig. 1). Agriculture represents over 90% of water withdrawals in India and sub-Saharan Africa (SSA) *[16]*. In SSA, 93% of agriculture is rainfed, representing 70% of the population's employment and 35% of GDP. SSA also has the least-developed water storage infrastructure needed to manage the variability of rainfall *[11]*. As a result, economic development in SSA remains particularly vulnerable to the vagaries of rainfall. While climate change may increase the challenge, already present climate variability is a major impediment to economic growth in SSA as a result of the large fraction of economies that agriculture represents and its vulnerability to climate anomalies.

Of the 183 million hectares of agricultural land in SSA, only about 9 million is under some form of water management *[62]*. While investment in expanding irrigation seems an auspicious way to improve agricultural productivity, estimates place the area of additional irrigation that would be profitable investments as part of dam-based schemes at only 3 million hectares *[36]*. For economic reasons then, small scale water management and storage approaches are likely to be a key component of efforts to increase agricultural productivity. The same preliminary IFPRI report estimates that small scale approaches might be profitable investments on an additional 38.2 million hectares. However, smaller-scale water management systems are best prospect for improving productivity under near-normal or moderately below-normal rainfall conditions. They are much less capable of managing climate extremes, such as floods and droughts. Farmers will continue to face considerable climate risk, and extreme events can reverse development gains made over many years. A single drought or flood could set back all the agricultural development progress that result from improved local water management. We term this remaining climate risk, "residual risk," and recommend that a strategy for investing in agricultural water management should include a multi-pronged approach to dealing with the full range of climate variability, including not only moderate years but also the extremes.

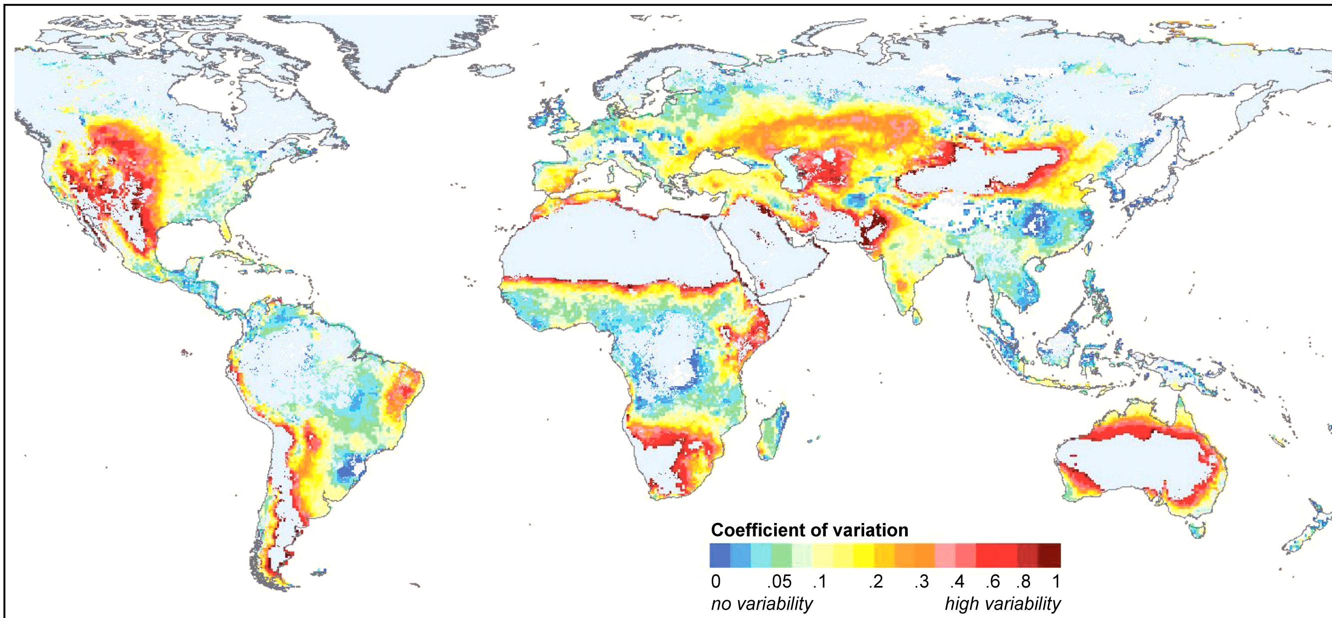


Figure 1. Year-to-year variability of length of growing period (LGP), 1960-1990. Source: *[59]*, adapted from *[85]*. LGP is the number of days per year in which moisture and temperature conditions will support plant growth. It is used as an indicator of moisture availability for rainfed production, and serves as a measure of farmers' likely exposure to climate risk.

1.1. Climate variability is an obstacle to agricultural development

A growing body of evidence links unmitigated hydroclimatic variability to poor economic growth in developing countries. Cross country analysis show that in most poor countries, climate variability is high, infrastructure in lacking and GDP is correlated with rainfall *[11; 25]*. In a study of climate impacts on economic growth of the countries of sub-Saharan Africa, drought was found to be the dominant climate risk, having a significant negative effect on GDP growth in one third of the countries *[12]*. Droughts are also the world's most expensive disaster, destroying the economic livelihood and food source for those dependent on the agricultural sector or their own food production *[87]*. The World Bank estimates that economic growth in Ethiopia is reduced by one third due to hydrologic variability *[88]*. A single drought over a 12-year period is estimated to reduce economic growth during the whole period by 10%. Drought impacts in Kenya associated with the La Nina of 1998 to 2000 resulted in losses totaling 16% of GDP.

Floods destroy infrastructure, disrupt transportation and economic flows of goods and services and can lead to contaminated water supplies and the outbreak of waterborne disease epidemics, such as cholera. In the Mozambique floods of 2000, over 2 million people were affected and damages were estimated at 20% of GDP *[31]*. Flood damages in Kenya associated with the El Nino event of 1997-1998 were estimated at 11% of GDP *[87]*. The effect of these hydrologic extremes can be devastating in any country, but especially in those with enhanced vulnerability due to high dependence on agriculture and deficient infrastructure. This is the case throughout SSA.

Climate exerts a profound influence on the lives of poor rural populations who depend on agriculture for livelihood and sustenance, who are unprotected against climate-related diseases, who lack secure access to water and food, and who are vulnerable to hydrometeorological hazard. Climate variability is arguably the dominant source of consumption risk in smallholder rainfed agriculture in the dryer environments of much of sub-Saharan Africa and India *[18; 83; 91]*. Within farming communities, because the relatively poor have less capacity to buffer against climate risk through own assets or financial markets, they tend to experience disproportionate livelihood risk in the face of climate variations. Current understanding of the mechanisms by which climate variability impedes agricultural development, and hence efforts to ensure food security and reduce rural poverty (Box 1), provides insights into opportunities for intervention.

The various mechanisms by which climate risk impacts households combine with other factors to trap rural populations in chronic poverty. A dynamic poverty traps occurs when there is a critical threshold of household assets, below which individuals are unable to accumulate the necessary resources to escape poverty *[3; 14]*. The tendency for risk tolerance to decrease with decreasing

Box 1: How does climate variability affect agricultural development?

Climate variability directly affects crop production, primarily by driving supply of soil moisture in rainfed agriculture, and surface water runoff and shallow groundwater recharge in irrigated agriculture. Because biological response is nonlinear and generally concave over some range of environmental variability, climate variability tends to reduce average yields.

Climate-driven fluctuations in production contribute substantially to volatility of food prices, particularly where remoteness, the nature of the commodity, transportation infrastructure, stage of market development or policy limit integration with global markets. Because market forces tend to move prices in the opposite direction to production fluctuations, variability in food crop prices tends to buffer farm incomes, but exacerbates food insecurity for poor net consumers.

The uncertainty associated with climate variability creates a moving target for management that reduces efficiency of input use and hence profitability, as management that is optimal for average climatic conditions can be far from optimal for growing season weather in most years. Crop responsiveness to fertilizer *[15; 57; 82]* and planting density *[1; 51]*, and hence optimal rates and profitability of production inputs *[38; 65; 78]*, varies considerably from year to year as a function of water supply.

Climate variability and risk aversion on the part of decision makers cause substantial loss of opportunity in climatically-favorable seasons as a result of the precautionary strategies that vulnerable farmers employ *ex ante* to protect against the possibility of catastrophic loss in the event of a climatic shock. Farmers' precautionary strategies – selection of less risky but less profitable crops *[17; 49]*, under-use of fertilizers *[8; 9]*, shifting household labor to less profitable off-farm activities *[69; 70]*, and avoiding investment in production assets, *[22; 61]* and improved technology *[39; 43]* – come at a substantial cost when climatic conditions are favorable.

Many of the coping responses that vulnerable households employ ex-post to survive an uninsured climate shock can have adverse, long-term livelihood consequences. Coping strategies that include liquidating productive assets, defaulting on loans, migration, withdrawing children from school to work on farm or tend livestock, severely reducing nutrient intake and over-exploiting natural resources, even permanent abandonment of farms and migration to urban centers or refugee camps, sacrifice capacity to build a better life in the future *[14; 19; 20; 45]*; see also review in *[6]*).

resource endowment *[17; 66]* contributes to the higher opportunity cost of climate risk for the relatively poor, and hence the locally-increasing marginal productivity that contributes to the existence of the multiple equilibria associated with a poverty trap *[3; 14]*. Ex-post coping response to severe or repeated climate shocks can push households to divest productive assets to a point below the poverty trap threshold *[19; 33]*. Climate risk also impacts institutions in a manner that further constrains economic opportunities and hence reinforce poverty traps at the household level *[5; 14]*. Examples include the increasing cost of food crisis relief competing with agricultural development for shrinking donor resources *[4]*, and the widespread reluctance of lenders to serve smallholder rainfed farmers.

While much is known about how climate risk impacts agriculture, less is known about the magnitude of the impacts or the magnitude of the livelihood benefits of feasible opportunities for managing climate risk (Box 2).

Despite the known impacts of current climate risk and growing concern about future climate change, climate risk management remains conspicuously absent from many analyses and regional development strategies. We speculate that this is because the agricultural community has long regarded climate as part of the environmental baseline and not a resource with options for management. Development strategies that recognize climate risk generally limit intervention to expanded irrigation or improved water management. The Comprehensive Africa Agriculture Development Program (CAADP), endorsed by the African Union, cites "vagaries of climate and consequent risk that deters investment" as one of six key challenges to achieving a productive and profitable agricultural sector across Africa. Its strategy for addressing this constraint emphasizes "extending the area under sustainable land management and reliable water control systems" *[52]*. However, recent assessments and strategies, such as the Comprehensive Assessment of Water Management in Agriculture *[16]*, increasingly recognize that feasible investments in water management for the drylands of SSA and parts of South Asia are necessary but not sufficient for overcoming the challenge of climate risk to development. **The infeasibility of achieving a high level of water control across the vast dryland farming regions of Africa in the near to medium term, and increasing stress on groundwater and surface water resources in much of India point to the need to exploit every opportunity to deal with the residual climate risk that water control systems cannot mitigate.**

Box 2: What does unmitigated climate risk cost agriculture?

Estimating the impacts of climate variability and of specific climatic extremes is simpler at an aggregate (e.g., national) scale than at household or community scales. Disentangling the various mechanisms of impact is even more difficult.

Grey and Sadoff (2006) estimated that the occurrence of droughts and floods reduces Ethiopia's economic growth by more than one third. Kenya suffered annual damages of 10-16% of GDP due to flooding associated with El Niño in 1997-1998 and La Niña drought in 1998-2000. These damages extended beyond agriculture, with 88% of flood losses incurred by the transport sector, while hydropower losses and industrial production totalled 84% of the drought losses *[86]*.

There is substantial information about how smallholder farmers respond to risk, but few comprehensive empirical analyses of the livelihood impact of those responses. For households within ICRISAT's village studies in India, Rosenzweig and Binswanger *[71]* estimated that climate variability (expressed as timing of monsoon onset) accounts for a 15% reduction of mean farm income for farmers within the median wealth class, and reduces income by 35% for farmers in the lower quartile of wealth, indicating that less wealthy farmers were more willing than their relatively wealthy neighbors to sacrifice income to buffer themselves against climate variability. A study of six villages in the Sahelian region of Burkina Faso showed that that variability of farm income (CV=0.25) leads to food shortfalls in one out of every five years for the average farmer, but four out of five years for farmers in the bottom quartile of land holdings, and only once in ten years for the top quartile of farmers *[13]*. Relatively poor farmers in these villages forego about 18% of their income to buffer against the existing level of risk (attributed primarily to climate variability), primarily by maintaining precautionary stores of grain, while the relatively wealthy farmers in the sample forego only 0.4% of income *[91]*.

Differentiating between the direct, ex-post impacts of climate-related shocks, and the cost associated with ex-ante decision-making in the face of climatic uncertainty is useful, as improved use of information has potential to reduce the latter. Model-based studies that compare returns to profit-maximizing management with and without knowledge of weather for the upcoming season provide an estimate of the cost of uncertainty in the absence of risk aversion. Climatic uncertainty costs the profit-maximizing farmer in Pergamino, Argentina, an estimated 23% of gross margin on average, and reduces the efficiency of N fertilizer use by 39% *[38]*. For a semi-arid location in Kenya, we estimated that the inability to anticipate daily rainfall for the growing season costs the profit-maximizing farmer an average of 41% of gross margin and 25% of yield. Elbers et al. *[21]* present a unique attempt to quantify both the ex-post costs of climate fluctuations and the ex-ante opportunity cost due to climatic uncertainty and risk aversion to a set of farmers. Combining 1980-2000 survey data from communal farm households in Zimbabwe with a dynamic household growth model, they attributed roughly one third of a 46% risk-driven reduction in 50-year wealth accumulation to actual ex-post losses associated with climate and other fluctuations, while the remaining two-thirds was due to ex ante responses to the associated uncertainties.

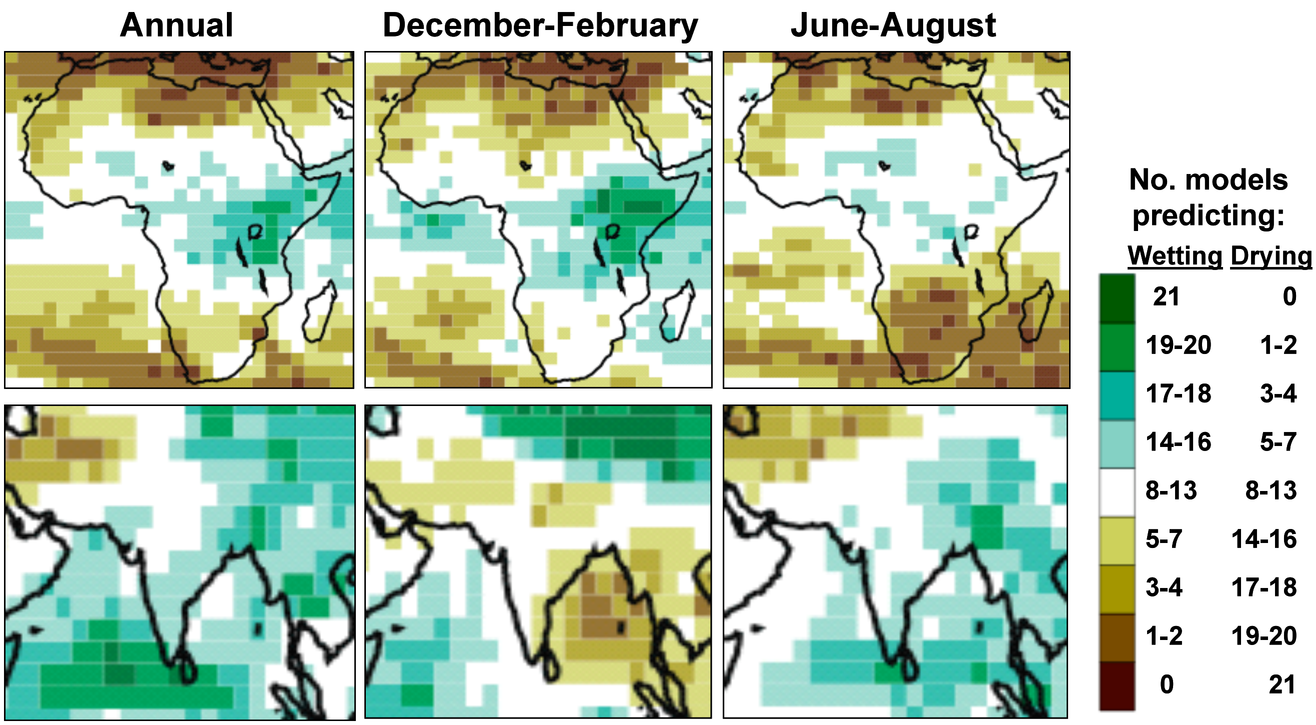


Figure 2. The degree of agreement about direction of changes in rainfall over Africa and India among the 21 GCM scenarios used in the 4th IPCC Assessment.

1.2. Climate change will intensify agricultural water challenges

Although the effects of climate change from anthropogenic forcing on the use of water resources in the world remain difficult to project *[41]*, **anticipated climate change combined with other drivers of change is likely to intensify current agricultural water management challenges in Africa and India**. The effects of population growth and increasing water demand, which are often but not always coupled, are likely to be a more significant source of water stress than climate change when considering changes to mean precipitation and runoff *[81]*.

Increasing temperatures in all regions are expected to increase evaporative demand, which would tend to increase the amount of water required to achieve a given level of plant production if crop phenology and management are held constant. However if cultivars and planting dates were to remain unchanged, accelerated crop development in response to temperature increases would tend to have the opposite effect on water requirements. Increased temperatures are also expected to increase evaporative losses of surface water resources.

The magnitude and even direction of projected changes in precipitation are quite uncertain. Based on how many of the 21 climate models used in the 4th IPCC assessment (AR4) predict increases vs. decreases in annual and seasonal rainfall across Africa and Asia (Fig. 2), decreased annual rainfall is very likely in Mediterranean North Africa and likely in much of Southern Africa particularly for the southern winter. Increases in rainfall are likely for much of Eastern Africa particularly in the northern winter, and for the summer monsoon over much of peninsular and eastern India. These climate models are divided between wetting and drying trends in most of West Africa and western India. The two models within this set that best captured the extended dry period (1970s-1990s) in the West African Sahel predict opposite response to projected greenhouse gas forcing *[7]*. There is, however, a consensus that **climate change will tend to increase the variability of rainfall and decrease the natural storage provided by snowpack and glaciers**, such as in the Himalaya that feed the rice-wheat belt of the Indo-Gangetic Plains.

The concern pertaining to climate change impacts should not overshadow the present challenges that climate variability poses to agricultural development. While the future impacts of climate change remain uncertain, climate variability persists as a challenge to development and as an impediment to meeting the Millennium Development Goals *[28]*. Over the next decades, while climate change trends may begin to have some effect, droughts and floods associated with climate variability will continue to ravage vulnerable communities in developing countries. Fortunately, there is much that can be done now to reduce that vulnerability.

2. Climate Risk and Agricultural Water Management

African countries and parts of India lack public or private infrastructure to provide storage to mitigate the variability of rainfall. Increasing the control of water resources is a direct method for managing the risk associated with climate variability and water storage is the most common approach to increasing water control. Storage options range from bunding and on farm impoundments to retain runoff from individual storms for supplemental irrigation, to large scale dams that can retain high flows, reducing the damage from floods and also providing water during dry seasons or droughts. In general, wealthy nations have invested in large scale storage infrastructure to achieve reliable water supply for domestic use and agriculture and for protection from extreme climate events, such as floods and drought (Fig. 3). An analysis of regional differences in the volume of storage relative to need indicates that the tropics generally, and the Caribbean, Africa and Asia specifically, have low levels of storage relative to need. It is apparent that the nations with the lowest per capita GDP have the greatest needs for additional storage. On average, less developed countries face greater climate variability and the resulting accumulated economic losses hinder their ability to invest in the storage needed to mitigate the variability effects *[11; 25]*.

2.1. Storage and reliability

The degree of water control that storage provides is a function of the size of the storage, the variability of the water flows and the magnitude of water demand. Large scale storage captures runoff from a distributed spatial area over which the heterogeneity of rainfall in space and time is smoothed. As a result, it is more reliable than storage that captures runoff from smaller spatial areas. Depending on the size storage volume, large scale storage may also accommodate a second growing season, provide protection from floods and generate hydroelectricity. However, environmental and often social costs often increase with storage volume, due to submerged areas that displace people or habitat. Historically, large scale irrigation schemes in sub-Saharan Africa have not paid off economically with low rates of return on investment. They have been plagued by high per hectare costs, low profitability, lack of transparency and lack of farmer involvement *[62]*. A study of 42 irrigation projects in sub-Saharan Africa found that between 1970 and 1984 projects were plagued by low rates of return (< 10 %) and high per hectare costs (averaging $24,500/ha), while projects implemented after 1984 showed some improvement *[62]*. Successful projects had per-hectare costs of $3000 - $5000 and many were rehabilitation projects. Preliminary research results from a study of the economic potential of irrigation investments indicates that major future investments in large scale irrigation are unlikely for economic reasons even considering "add-ons" to existing dams or those to be built for hydroelectricity and flood control *[36]*. In contrast, small scale and community managed irrigation have been generally more successful, although most existing studies were completed at the pilot scale only *[62]*. A variety of studies have examined the economic viability of various approaches at local scales *[23; 35; 40; 53]* but there are few studies of there reliability in response to climate variability at a planning perspective (Box 3).

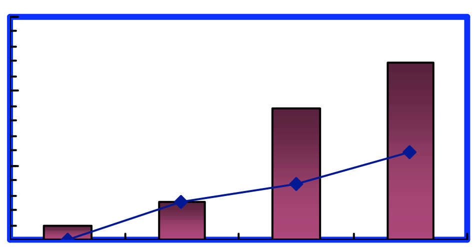


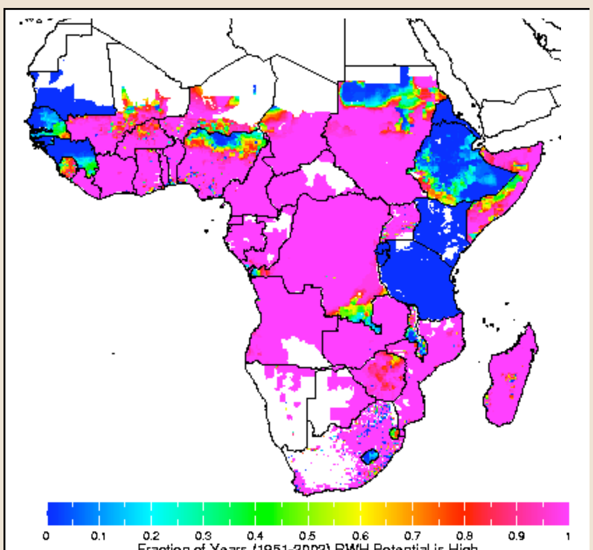
Figure 3. Current water storage as percent of need for the countries of the world, categorized by per-capita GDP. Very poor countries have low percentage of their need, while wealthier countries have more than they need. Storage need is determined by water demand and the variability of rainfall.

Smaller scale storage offers the benefit of more local control and less externalities in terms of submerged area. Pilot studies of surface impoundments (farm ponds) in Kenya and Burkina Faso have found significant potential increases in yield and productivity through supplemental irrigation and extending the growing season *[23; 53]*. Improved water control may also be achieved through methods that focus on the control of evaporation, such as conservation farming, drip irrigation, furrowing and leveling of fields. These methods have also tended to be the most economical, although there exists low rates of adoption for reasons that are not entirely understood. In the Kenya study, one factor was the high rate of water loss due to seepage and evaporation *[23; 53]*. Cost estimates for these approaches are wide ranging and overlap with the estimates of the most economical large scale projects. In a forthcoming report, IFPRI estimated the cost of traditional methods such as water harvesting at $600 to $1,000/ha, individual irrigation systems such as pumps and distribution lines at $1,500 to $3,000/ha and community level irrigation, including small dams, at $3,000 to $8,000/ha.

Box 3: Estimating the reliability of rainwater harvesting

Rainwater harvesting (RWH) has a long lineage and has likely been practiced where ever rainfall was variable and needed *[72]*. It is promoted as a climate change adaptation strategy and as a key strategy for better water management in developing countries *[47; 58]*. However, the potential for RWH as an effective adaptation strategy has not been assessed except at the micro scale *[23; 53]*. Several analyses have considered the role of RWH to provide drinking water in urban areas including storage requirements and reliability estimation for particular locations *[42]*.

Brown et al. *[12]* use global data sets to estimate the reliability of rainwater harvesting based on per capita water demand and gridded population data, at a resolution that is useful for assessing rainwater harvesting potential. While the analysis cannot predict where RWH will succeed, it demonstrates the importance of the different timescales of rainfall variability for local water management interventions such as rainwater harvesting. Results (see figure) reveals a wide area where rainwater harvesting has potential to provide the full storage needs of rainfed agriculture in Africa. In these areas, total rainfall is sufficient to provide crop requirements, but intra-seasonal dry spells – which RWH is a well-suited to mitigate – may impact crops. In parts of Africa, notably in Ethiopia, Kenya and West Africa, where monthly rainfall in the average year is not sufficient to meet water requirements, RWH will still reduce susceptibility to intra-seasonal dry spells, but may not be sufficient to provide all the water needed. Other methods of mitigating rainfall variability, including large scale storage, may be more promising there.



RWH Reliability Map, showing percent of years where RWH is sufficient to meet agricultural water needs. North Africa and areas with low population densities are masked (white).

2.2. Residual climate risk for agricultural water management

The reliability of water supply is a key factor in the success of interventions to improve agricultural productivity *[62]*. Since water supply is less reliable at local scales, and water management investments are most likely to be made in local scale approaches, due to the economic reasons cited above, consideration of the climate risk that is not covered by these approaches is warranted. We label this remaining risk "residual climate risk."

Increasing the control of water resources available for agriculture reduces vulnerability to climate variability and leads to greater agricultural productivity. Water management strategies differ in the range of climate variability they are able to control. Local water management approaches provide mitigation of slight or moderate departures from normal rainfall, but are limited in mitigating more severe anomalies, such as droughts or extended dry spells. Because the drainage area over which runoff is collected is smaller, the reliability would on average be reduced.

Rainfed agricultural systems, which represent 93% of SSA agriculture, are highly vulnerable to climate variability. Soil management approaches, such as conservation farming, may improve productivity in near normal and below normal rainfall years. In Kenya, tied ridges increased yields on average, but are economically viable only in seasons with moderately low rainfall, as yield increases do not cover the added setup costs when rainfall is either very high or very low *[24; 76]*. Thus, such approaches leave residual climate risks including dry spells during critical growing periods, droughts, and lack of protection from floods.

Farm scale irrigation systems, such as groundwater irrigation and on-farm surface water collection, and community-managed systems, reduce the vulnerability of farmers to dry spells and intra-seasonal rainfall variability through supplemental irrigation and may allow extension of the growing season *[62]*. A pilot scale study of farm ponds in Kenya and Burkina Faso found them to be profitable, but included a limited range of rainfall variability during the three year study *[23]*. A similar study in Kenya determined that losses from evaporation and seepage limited their effectiveness and may have contributed to the low rate of adoption there *[53]*. Because the catchment area of on-farm water collection systems is relatively small, they are less able to mitigate the spatial heterogeneity of rainfall and thus water supplies are less reliable than larger scale efforts. Residual climate risks include drought and floods. Groundwater irrigation may provide protection from drought and dry season farming, depending on the depth to water and the volume of the aquifer, and its potential application within Africa is not well known. Experience from India makes clear that groundwater can be a boon to agricultural production but also is vulnerable to overexploitation *[73]*.

Large-scale public irrigation system are surface water systems typically with large storage volumes collecting water from sizeable contributing areas and delivery systems covering a large area. These systems are designed to provide resilience to most droughts and to allow multiple cropping seasons and provide the highest potential protection against climate risks. Still, actual reliability of water supply for an individual farmer depends on one's location and priority within the system. For example, reservoir systems where water is shared with drinking water supply systems and hydroelectricity production often place the lowest priority on agricultural water and the reliability of agricultural water deliveries is compromised. Because the cost of dam construction is so large, recent studies indicate that irrigation expansion via dams will only be economical where the primary water use is hydroelectricity generation *[36; 62]*. The residual climate risks of these systems then include extreme or multiyear droughts and competition for water resources with hydroelectricity and drinking water during times of scarcity.

3. Managing Residual Climate Risk

In the drylands of SSA and parts of Peninsular India, where much of the remaining hunger and poverty are concentrated, "the key challenge is to reduce water-related risks posed by high rainfall variability rather than coping with an absolute lack of water" *[16]*. Yet the most viable opportunities for improving agricultural water management offer only incomplete control. A holistic strategy for investing in pro-poor agricultural water management requires parallel investment in other climate risk management measures to deal with the residual risk that water control alone cannot mitigate.

Climate risk management for agriculture includes:

- Systematic use of climate information and climate knowledge in strategic planning (e.g., water control design, breeding) and adaptive decision making;
- Climate-informed technologies (e.g., agricultural water management, drought-tolerant germplasm) and management strategies (e.g., livelihood diversification) that reduce vulnerability to climate variability;
- Climate-informed policy (e.g., early warning and response systems, safety nets) and market-based interventions (e.g., insurance, credit) that transfer risk from vulnerable rural populations.

Climate risk management must address the full range of variability, balancing protection against the impacts of climatic extremes such as droughts and floods (extreme left tail, Fig. 4) with effort to capitalize on opportunities arising from average and favorable climatic seasons (roughly 2/3 of the area toward the right, Fig. 4).

While improved water management is a crucial element, a portfolio of synergistic interventions is the most promising approach to covering the full spectrum of climate risks that confront farmers and impede the investment needed to realize the potential benefits of water management. Several options are available for managing the risk that feasible water management strategies cannot cover. A few – new ways to use new types of climate information, climate-informed livelihood strategies, innovations in financial risk transfer products – have not yet been fully explored or exploited.

3.1. Managing agriculture for resilience

In addition to investment in agricultural water management technologies, breeding for drought stress and diversification strategies can reduce vulnerability to moderate fluctuations in rainfall. Much of crop germplasm improvement targeting the tropical drylands is focused on resistance to drought and associated stresses. While drought-resistant germplasm development is fairly well established and supported relative to some of the emerging areas of climate risk management, there is still controversy about whether improving yields under drought must come at the expense of yields in seasons when rainfall is favorable. Livelihood diversification can be an effective means to increase resilience in the face of climate variability if (a) the

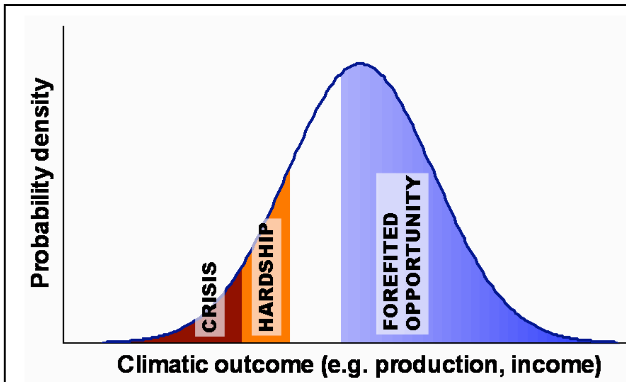


Figure 4. Idealized representation of impact of climatic risk associated with different portions of the distribution of some climate-sensitive outcome. After *[30]*

different income streams are not strongly correlated with each other or with seasonal rainfall, and (b) the diversified portfolio does not sacrifice substantial average income. Opportunities for diversification can range from mixes of cultivars with staggered phenology at the field scale, to mixes of farm and non-farm enterprises across the household, to more diverse rural economies. Investment in rural roads, market infrastructure and education are likely to foster greater diversification. Risk analysis, using historic climate data and standard analytical methods, can inform the design of more resilient diversified management strategies. There is also scope for such analyses to tailor germplasm development to small-scale water management such as conservation farming, and to mixes of cultivars that are less susceptible to dry spells than single cultivars.

3.2. Use of climate information by rural communities

To the degree that climatic uncertainty adversely impacts farmer livelihoods, climate information that reduces uncertainty has potential to improve livelihoods. Relevant information includes historic climate records, monitoring of the current season, prediction at a range of lead times, and value-added information which integrates and translates raw climate data into impacts and management implications within agricultural and hydrological systems. Seasonal prediction is a particularly promising yet largely unexploited innovation in those regions and seasons (Fig. 5) where interactions between the atmosphere and underlying ocean and land surfaces provide a degree of predictability of rainfall at a seasonal (i.e., ≥ 3 months) lead time. The lead time of seasonal forecasts matches the period between the many climate-sensitive decisions (e.g., allocation of farm land and household labor, choice of crops and production inputs, financing and procurement arrangements) that must be made prior to planting, and harvest when outcomes of those decisions are realized. When the necessary conditions are in place *[27]*, seasonal forecasts provide farmers the opportunity to adopt improved technology, intensify production, replenish soil nutrients and invest in more profitable enterprises when conditions are favorable or near average; and to more effectively protect their families and farms against the long-term consequences of adverse extremes.

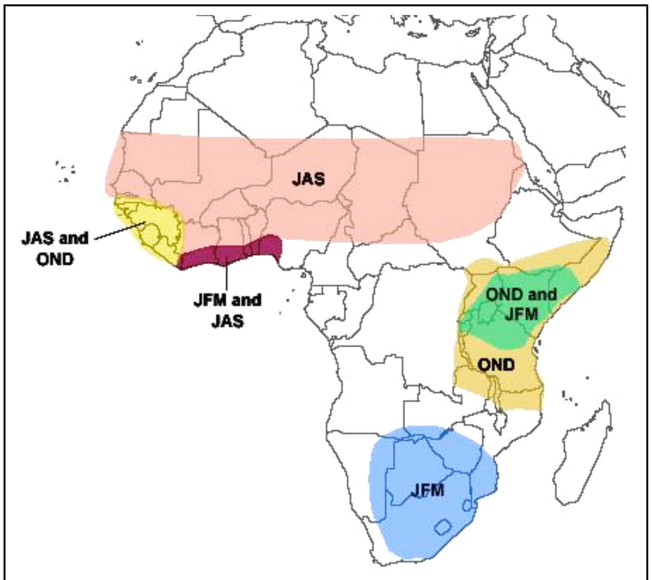


Figure 5. Regions and seasons in Africa with established seasonal rainfall predictability.

Local historic climate records provide a means to quantify climate risk when making strategic investment and design decisions (e.g., water storage or irrigation infrastructure), and when adapting new technologies to a local environment. Downscaling seasonal forecasts locally and interpreting inherently probabilistic forecasts in the context of historic variability require long-term records. There is anecdotal evidence that biased perception of climate change – either underestimation of real change or overestimation of weak or non-existent trends – can contribute to poor management of rainfed agriculture. Routinely consulting climate observations provides a means to correct biases and to adjust management incrementally to adapt to progressive change. Real-time monitoring and prediction at a weather (i.e., ≤14-day) time scale contribute to food security and hydrometeorological (e.g., flood) hazard early warning systems. However information at these lead times are generally established within farmers' indigenous knowledge and observation, or accessible through existing services (e.g., weather forecasts, agrometeorological bulletins).

With few exceptions, the provision of climate information services to rural communities and other agricultural stakeholders (market institutions, government planners, food security response organizations) remains woefully inadequate throughout sub-Saharan Africa and India. Seasonal climate forecasts have been disseminated routinely for the past ten years through regional climate outlook forums in much of Africa. Studies of the use and value of seasonal forecasts for smallholder agriculture reveals a high level of awareness and interest, and a range of promising management responses *[54; 77; 90]*. They have also identified obstacles associated with communication failures *[2; 37; 55; 63; 90]* or resource constraints that limit capacity to respond *[37; 54; 63; 64; 80]*. Constraints related to communication are, to a large degree, symptomatic of inadequate policies and institutional process, and therefore potentially amenable to intervention. Adoption rates and reported benefits have been fairly high in pilot projects in Zimbabwe, Burkina Faso and India and where extended interaction between smallholder farmers and researchers overcame some of the communication barriers *[34; 46; 60; 68]*.

The gap between current climate services in Africa and the needs of development is not limited to seasonal forecasts, although they have been the most studies. A multi-stakeholder, cross-sectoral assessment of the use of climate information in Africa concluded that (with a few noteworthy exceptions) the gap pervades across sectors and from local to policy levels, and attributed it in part to "market atrophy" resulting from the interplay between ineffective demand by development stakeholders and inadequate supply of relevant climate information services *[28]*. Several gaps need to be addressed in parallel if climate information is to contribute to development at the scale of the MDGs (Box 4).

3.3. Innovations in financial risk transfer

Recent innovations have resulted in a resurgence of effort to manage risk through insurance and other financial risk transfer instruments for smallholder rainfed agriculture in developing countries. Basing insurance payouts on an objectively-measured index (e.g., rainfall amount, modeled water stress, area-averaged production) that is correlated to loss instead of actual losses, overcomes problems with moral hazard (i.e., incentive for farmers to let crops fail), adverse selection (less skilled farmers preferentially purchase insurance) and high transaction costs that have generally made traditional insurance unviable for smallholder farmers in developing countries *[6; 32; 44; 74; 79]*. However, it introduces basis risk: the residual uninsured risk that results from the imperfect relationship between the index on which payouts are based and the losses that the insurance is meant to protect against. Because index insurance does not protect against all risks, it must be carefully designed as a component of a comprehensive risk management policy *[50]*.

Index insurance and associated financial products are being applied in several innovative, non-traditional ways to reduce particular climate risk-related constraints to agricultural development and rural poverty reduction. The World Bank's Commodity Risk Management Group is working with partners in several African and Latin American countries to implement bundled index insurance-credit-production input packages that overcome barriers to adoption of more profitable, intensified production technology by targeting the risk aversion of lenders *[32; 56]*. The World Food Program is working with the Ethiopian government on an index-based insurance project that would provide more timely access to funds to respond to emerging drought-related food crises *[75]*. Barrett et al. *[6]* provide a critical review of applications of index-based risk transfer products to reduce poverty, and propose a typology of applications based on where populations fall within a dynamic poverty trap framework.

Because some of the key obstacles to up-scaling index insurance for farmers and food crisis response relate to climate data *[6]*, index-based insurance is increasing demand for climate information in data-sparse regions.

3.4. Anticipating and responding to climate-related crises

Climate variability imposes episodic extremes that even large-scale irrigation systems cannot mitigate, and that overwhelm the coping capacity of local populations without

Box 4: Priorities for strengthening climate information services in SSA

Institutional development to: (a) realign NMS from gatekeepers of data, to providers of services for development and participants in the development process; (b) ensure that products and services are driven by the needs of agriculture; (c) reform policy to make climate data available as a public good and resource for development; (d) revitalize and engage agricultural extension as providers of climate information and knowledge; and (d) coordinate response between farmers and their advisers, market institutions, water managers and food crisis response organizations.

Observations and infrastructure investment to: (a) reverse decline in observing systems; (b) rescue and digitize paper records; (c) supplement sparse observations with merged remote sensing – station data sets; and (d) enhance remote sensing products by extending duration (~30 years now possible), improving calibration, and correcting daily interpolation bias.

Information products designed (content, scale, format, timing) to meet known farmer needs; refined for particular contexts through ongoing stakeholder participation; with continuing investment in value-added products (e.g., predictions of crop and forage yields, streamflow, flood hazard, pest and disease risk) for institutional users.

Delivery mechanisms that integrate climate information as a routine part of agricultural extension (where functional); underpinned by training for intermediaries and by agricultural research; which foster farmer interaction and co-learning. Investment in rural communication infrastructure (radio, ICT) is also needed both as an alternative vehicle to reach rural communities and to streamline information transfer to communication intermediaries (e.g., district agricultural offices).

Evidence of development impact for rural climate information services, needed to mobilize resources and institutional support. Weak body of evidence relative to other agricultural development interventions is due to: (a) newness of seasonal prediction, (b) lag time required to quantify impact particularly in the face of a stochastic driver, (c) widespread institutional failures that have constrained use beyond pilot projects, (d) neglect of impact assessment by proponents, and (e) early studies that identified, but didn't seek to overcome, constraints to using existing operational products.

either outside intervention or high long-term cost to livelihoods.

Advance estimates of staple crop production are an essential input to a range of contingency planning, food crisis management and market applications. Early information about production shortfalls is a necessary but not sufficient condition for effective response, as delay in initiating response greatly increases the humanitarian and livelihood impacts of a food crisis, and the cost of aid *[6; 10; 26]*. Because climate-related fluctuations in production can have large impacts on price and hence accessibility of staple foods, the use of production forecasts to manage markets and strategic grain reserves to stabilize prices is an appealing food security intervention.

The best-developed applications of climate information for risk management in SSA are for food security early warning and response. FEWSNET, JRC, FAO, WFP, AGRHYMET, SADC/RRSU and some countries have developed or routinely apply similar suites of spatial tools – rainfall monitoring, satellite vegetation monitoring, simple water balance-stress index models that incorporate historic and monitored weather data – to estimate food crop production shortfalls in advance of harvest. These approaches have not yet successfully integrated the use of seasonal climate forecasting. For much of SSA especially, where there is potential forecasting skill in many regions and seasons, this represents a major opportunity to improve the lead time and consequently the performance of food security early warning systems.

The apparent increase in the frequency and extent of major flood events, whether due to land use changes, increasing vulnerability or climate changes, has created new interest in measures to reduce flood impacts. Beginning in 2003, the World Meteorological Organization convened a series of workshops to assess the status of flood forecasting systems throughout the world. Their findings indicated a wide range of capabilities (WMO, 2006). The countries of west and central Africa had the most limited systems, due to shortages in real time data and observation networks, poor integration of climate data into hydrologic models and insufficient skills among weather and hydrologic services' staff. Some regional efforts are underway, through for example, AGRHYMET and the Niger Basin Authority, but since warning and response services are typically organized nationally, they do not replace the need for national level services.

In southern Africa the situation varies widely between countries, some with no operational systems and some pockets of good collaboration between meteorological and hydrological services. There is an absence of hydrologic forecasting in some countries for many of the same reasons that affect west and central Africa, including lack of data networks and skilled staff. The report by WMO summarizes the key challenges for improving flood forecasting systems in all regions. Among the most prominent are the need for better observation systems and communication networks and the improvement of meteorological and hydrological forecasting products *[84]*.

Throughout Africa, there is a lack of flood risk mapping. Due to the dearth of hydrologic observation stations and damage to the few stations during flood events, there is no systematic record of flood events. As a result, there is a lack of ability to estimate flood risk exposure or to map flood risk. Currently, only anecdotal evidence is used to estimate flood risk *[87]*.

Experience from the devastating floods of Mozambique provide further guidance on the importance of communication systems for transmission of flood forecasts, where operational flood forecasts actually exist (Hellmuth, 2006). Mozambique has a history of extreme floods as it is positioned on the coast in the path of tropical storms and downstream of nine major river basins. There have been seven major floods since 1980 which instigated government and donor response for the development of operational flood forecasting. In 2000, seasonal forecasts shaded toward above average rainfall and flood warnings were issued. However, there were several sources of flood forecast information and in some cases they were contradictory. In general, communication to the public was poor. Since then, investments have been made in hydrologic observation stations, community-based risk management and the mass media has been recognized as a key transmission route for flood warnings.

4. Opportunities for New Investment

This report has reviewed the effect of climate variability on agricultural development in general and agricultural water management in particular. The findings indicate the limitations of singular strategies to manage the climate challenges to agriculture. While local water management can improve agricultural production in near normal years, it leaves farmers vulnerable to droughts and offers little advantage to exploit the opportunities of above normal rainfall years. This may be a factor in why adoption rates are surprisingly low.

Better results in agricultural development might be achieved by considering and managing the full spectrum of climate risk. A key underexploited opportunity is the use of climate information, including historical data, monitoring and prediction, to improve the design, operation and response of agriculture systems for resilience to climate variability and change. In this section, we highlight three specific opportunities that we consider promising. Each targets a different layer of risk:

- Climate-informed investment in water management to increase the resilience of agricultural development and stimulate investment;
- Rural climate information services to support adaptive management of water and production activities, as a way to manage residual risk with incomplete water control; and
- Integrated early warning systems to support more timely and better coordinated response to climatic shocks that exceed the coping capacity of rural communities.

4.1. Accounting for climate variability in small-scale water management

The case is clear for the need for better management of agricultural water resources in SSA and India, and in SSA especially, increasing the reliability of water supplies through water storage. Several studies have evaluated the cost effectiveness of small scale versus large scale storage investments *[23; 36; 88]*, the reasons for low adoption of small scale storage methods *[40; 53]*, and the effects of irrigation on poverty *[35]*. However, there is little consideration of the optimal combination of large and small scale storage to meet the particular climate variability challenge for a river basin, region or nation from a macro-scale (one example is a study of vulnerability that groups countries very broadly by rainfall season length and internal resources *[89]*. In fact, the use of climate information in these studies is lacking, as is any recognition that the climate challenges are significantly different depending on location and water demand (see Box 3). Yet, these measures are all, in theory, a response to climate variability.

Given the interest among donors and governments to increase investment in agriculture, and in water storage in particular, there is a major opportunity to coordinate and shape these investments such that they represent the best use of limited resources to manage the climate variability faced. A systems analysis approach to the design of water infrastructure was the hallmark of the Harvard Water Program, which began as a multidisciplinary attempt to address irrigation problems in the Indus River valley *[67]*. The systems analysis approach, while still relevant, requires updating in its understanding of climate. Like all water management practices, the approach is based on the assumption that climate is stationary *[48]*. Additional innovations that can augment traditional approaches include the complementarities of small scale and large scale storage, the use of climate forecasts and monitoring, and the ability to manage risks financially through risk transfers at the microscale and macroscale. An updated systems analysis approach to designing resilient water systems can be accomplished by identifying how climate affects agricultural production, characterizing the nature of climate dynamics at the scale of analysis, and using this information to create an integrated water management system that address the full spectrum of climate risks to agricultural development. The process consists of the following steps:

- Assess current and historical impacts of climate variability on agricultural production and farmer welfare. This would be conducted using historical climate and economic data, which would be integrated in a GIS platform allowing the identification of climate risk “hotspots” and regions of enhanced vulnerability as well as opportunities.

- Characterize the hydroclimatic risk profile for the area of interest through analysis of historical climate data and model output. Topics to be addressed include: what are the probabilities and return periods of hazard causing climate events? Are there trends or periodicity? Is there codependency between spatial extent and severity of climate anomalies? Is there predictability on seasonal timescales or clear direction in climate change projections?

- Based on the understanding developed in the preceding steps, design an integrated water management system, grounded in the principles of integrated water resources management and developed in collaboration with stakeholders, for optimal investment. Water “supply curves,” which represent an ordering of water supply options according to the unit cost for a given reliability will be calculated and serve as guiding frame for investment selection within a systems analysis approach.

- Identify and manage residual risk through complementary use of non water interventions. Systematic analysis will identify remaining risks not covered by water management strategies. Non water interventions for improving agricultural resilience are identified to address vulnerabilities. Examples include the use of climate information, including seasonal forecasts for identifying climate opportunities, and index insurance and early warning systems to protect against climate extremes.

The scarce consideration of climate is not unique to agricultural water management. In fact, the entire water management community is grappling with a response to growing understanding that climate is not stationary. A major part of that response should be based in the use of available climate information both in the planning and design of water management systems, as outlined above. Currently a gap exists between operational water management and climate information. It will likely persist unless the use of climate information is integrated into water system design. This is vitally important in agricultural water management where infrastructure is lacking and climate is especially variable, i.e., SSA, because the vulnerabilities are so widespread.

4.2. Rural climate information services

There is substantial opportunity for targeted investment to overcome known obstacles to delivering relevant climate information products and effective information and advisory services for rural communities where complete water control is not feasible in the foreseeable future. We recommend targeting investment to fill gaps across the full suite of interventions needed to make rural climate information systems work. For countries in SSA, this would generally include parallel investment:

- Investment in climate data sets – potentially including digitizing paper archives, improving data storage and management, using remote-sensing to filling gaps in space and time, and negotiating data-sharing arrangements;
- Work with the NMS to design downscaled, tailored seasonal forecast products, and develop software tools and institutional capacity for sustained implementation.
- Development of curriculum and an in-service training program in climate information communication and risk management for agricultural extension and effective NGO counterparts;
- Support for initial implementation of forecast training and dissemination workshops, evaluation of use and benefit, and participatory refinement of products and services at a pilot scale.

Depending on the country, some negotiation or investment in ICT may be needed to ensure a streamlined process for distributing climate information e.g., to district agricultural administration offices.

A key outcome is agricultural extension services empowered to routinely convene the rural community (or their representatives) prior to the start of the growing season to present seasonal forecasts, discuss variability and any evidence of trends from the historic record, review previous season management and climatic outcomes for any lessons, discuss conditions monitored so far (e.g., early rains, soil moisture, traditional indicators), and discuss management for the coming season.

We suggest investing initially at an intermediary scale that is large enough to foster significant change in institutions (NMS, NARES), and building careful impact evaluation into the effort from the onset. There is a tradeoff between investing at sufficient scale to have an impact on poverty and food security vs. testing interventions at a pilot scale long enough to collect credible evidence of benefit.

Degree of predictability (of the short rains) at a long lead time, and strength of regional institutions (e.g., ICPAC, ASARECA) favor starting in the portion of eastern Africa that includes much of Kenya, Ethiopia, Uganda and northern Tanzania. The most promising opportunities are in semi-arid regions that are dominated by rainfed, cereal-based mixed farming systems. Kenya has a strong national agricultural research system (NARS). The effectiveness of the formal agricultural extension system varies, and is often constrained by inadequate resources (e.g., transportation, ICT infrastructure). The Arid Lands Resource Management Program (ALRMP), supported by World Bank and housed in the Office of the President, has a mandate for drought management and capacity to serve an extension and communication role at at-least a pilot scale. The NMS hosts and collaborates closely with the regional climate center (ICPAC). Ethiopia also has a reasonably strong NARS. Recent decentralization and investment in rural development has strengthened the agricultural extension system. With support from Google.org, Ethiopia is preparing to develop long-term (30-year), high-resolution, merged satellite-station meteorological data sets intended to support development. Uganda has a similar fiscal and governance decentralization policy, and also benefits from strong farmer associations. We have less experience with Tanzania.

4.3. Integrated early warning systems

Despite the best investments in agricultural water management and the best use of rural climate information services, a small number of extreme climate events will overwhelm the ability of farmers to cope. These events, though rare, can have devastating impacts on rural development efforts. Early warning and response systems can help mitigate the impact of these events by providing farmers, government agencies and NGOs valuable time to prepare for and respond to extreme floods and droughts. However, the full potential of climate monitoring and forecasting has not yet been integrated with existing flood, drought and food security early warning systems.

Because the proportion of total uncertainty that is due to climate decreases through the growing season, the relative benefit of climate prediction (decreases in importance through the season) and monitoring (increases in importance) depends on the timing of the crop forecast *[29]*. In most cases, accuracy (at a given lead time) or lead time (at a given level of accuracy) can be improved by incorporating additional information. Early warning systems often treat satellite vegetation indices (NDVI and its derivatives) as a complement to model-based estimates of yield loss from water stress. Assimilating vegetation indices within model-based crop monitoring and forecasting systems can reconcile and optimally combine the two sources of information. Several methods (reviewed in *[29]*) are available for incorporating seasonal climate forecasts into model-based crop yield prediction. Improvements in long-term, high-resolution, merged satellite-station data sets are expected to improve accuracy of model-based yield estimates. Increasing the length of rainfall proxy records that go into calibration will allow crop production monitoring and forecasts to be expressed in probabilistic terms, and the tradeoff between lead time and accuracy to be made explicit. In contexts where drought stress is not the dominant climatic cause of yield losses, modeling additional yield-limiting factors is expected to improve prediction.

The variety of crop production early warning systems that are operational complicates the decision about where to invest. In SSA, we prioritize regional technical institutions that have the political mandate to serve their member states. In West Africa, the AGRHYMET Regional Center is looking to make several enhancements to their operational crop monitoring system, and to expand their services from the CILSS (Sahelian) countries into all the countries that are part of ECOWAS. SADC/RRSU has the mandate in Southern Africa, but would need to be strengthened considerably as an institution before technical enhancements would be effective.

A WMO review of flood forecasting systems globally identified priority action areas for improving early warning systems *[84]*. Prominent among these is the need for strengthening of observing and information systems. This includes meteorologic and hydrologic station networks, real-time data transmission and hydrometeorologic communication systems. Satellite-based observation offers potential for improving identification of inundated areas and can complement hydrologic modeling, but forecasting depends on ground based observations for calibration and validation of predictions. The merging of ground based and satellite based observation systems is a promising opportunity for flood forecast improvement. Further still, the combination of seasonal climate forecasts with lead times on the order of months with continuous monitoring for rapid detection of high risk areas has yet to be accomplished, although the technology exists.

The lack of historical observations contributes to the uncertainty regarding flood risks throughout Africa. There is no historical database of flood events, other than anecdotal, and as a result, no hydrologically-based maps of flood risk. Methods now exist to use historical observations of climate data, including global rainfall datasets and satellite-based digital elevation models in combination with hydrologic models to create synthetic historical estimates of flood risk and corresponding flood risk maps. Such maps would be valuable in planning water storage investments and planning for warning systems and response.

The lessons learned in Mozambique and the gaps in flood warning capabilities in many countries as outlined by the WMO reveal ample opportunity to reduce the risk of devastating floods on agricultural communities. Characterization and mapping of flood risks, improved observation systems, development of flood forecasting skills and hazard communication systems are promising areas of investment for many poor countries in Africa and in regions of India, notably Bihar. Without such efforts, farmers and many others remain vulnerable to floods striking without notice and destroying the hard won development gains accomplished through years of incremental improvements, such as agricultural water management.

There are a variety of opportunities to improve integrated early warning and response systems for hydroclimatological hazards. There are promising opportunities to exploit technological advances including remotely observed and modeled climate and environmental data. Priorities for investment include:

- Characterization of historical risk and uncertainties associated with hydroclimatological hazards
- Merging of environmental monitoring and seasonal climate forecasting with modeling to improved forecasts of floods and famine

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[i] Dryland agriculture refers here to agriculture in sub-humid to arid rainfall regimes that is not under reliable irrigation.