Climate risk management and rural poverty reduction

Article

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Climate risk management and rural poverty reduction

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ABSTRACT

Climate variability is a major source of risk to smallholder farmers and pastoralists, particularly in dryland regions. A growing body of evidence links climate-related risk to the extent and the persistence of rural poverty in these environments. Stochastic shocks erode smallholder farmers' long-term livelihood potential through loss of productive assets. The resulting uncertainty impedes progress out of poverty by acting as a disincentive to investment in agriculture – by farmers, rural financial services, value chain institutions and governments. We assess evidence published in the last ten years that a set of production technologies and institutional options for managing risk can stabilize production and incomes, protect assets in the face of shocks, enhance uptake of improved technologies and practices, improve farmer welfare, and contribute to poverty reduction in risk-prone smallholder agricultural systems. Production technologies and practices such as stress-adapted crop germplasm, conservation agriculture, and diversified production systems stabilize agricultural production and incomes and, hence, reduce the adverse impacts of climate-related risk under some circumstances. Institutional interventions such as index-based insurance and social protection through adaptive safety nets play a complementary role in enabling farmers to manage risk, overcome risk-related barriers to adoption of improved technologies and practices, and protect their assets against the impacts of extreme climatic events. While some research documents improvements in household welfare indicators, there is limited evidence that the risk-reduction benefits of the interventions reviewed have enabled significant numbers of very poor farmers to escape poverty. We discuss the roles that climate-risk management interventions can play in efforts to reduce rural poverty, and the need for further research on identifying and targeting environments and farming populations where improved climate risk management could accelerate efforts to reduce rural poverty.

1. Introduction: climate risk and rural poverty

Significant gains in food security and rural poverty reduction, associated with the Green Revolution, resulted from a combination of investments that increased production, reduced risk and enhanced market access. Subsidized inputs, such as irrigation, reduced the production risk faced by farmers and in part account for their willingness to invest in increased on-farm production and productivity. Because agricultural development efforts in the 1960s–1980s focused more on intensification of favorable areas than on the constraints in more marginal and risk-prone environments, the Green Revolution's contribution to rural poverty reduction was less evident in marginal production environments (Pingali, 2012). Despite continued efforts to improve farmer's living standards, poverty and food insecurity are still prevalent across large portions of sub-Saharan Africa and South Asia. Prevalence is often high in the drylands (i.e., rain-fed areas in dry sub-humid to arid agro-ecological zones), where climate variability exposes smallholder farmers and pastoralists to major risk (Hyman et al., 2008; Dercon, 2002; Walker and Ryan, 1990; Zimmerman and Carter, 2003). Today, there are increasing calls for a second Green Revolution targeted at regions with precarious agricultural conditions such as Sub-Saharan Africa. A central challenge is to go beyond increased agricultural production per se, and mitigate risks posed by increasing variable climate and marginal production conditions to ensure that large numbers of farmers move out of poverty and increase rural prosperity.

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Climate-related disasters impact poor countries, and the relatively poor within countries, disproportionately (Carter et al., 2007; Easterly, 2001; Gaiha and Thapa, 2006). In the face of a severe climate shock, such as a drought, flood or heat wave, vulnerable households employ a range of ex-post strategies to cope with the resulting crisis, including: liquidating productive assets, defaulting on loans, withdrawing children from school to work on farm or tend livestock, reducing nutrient intake, and over-exploiting natural resources. Although these coping strategies enable households to endure a crisis in the short term, they often reduce the household's capacity to build a better life in the future by eroding productive assets (Barrett and Carter, 2001; Carter and Barrett, 2006; Carter et al., 2007; Dercon, 2004; Dercon and Hoddinott, 2005; Hoddinott, 2006; McPeak and Barrett, 2001; Wood, 2003) and human capital (Alderman, et al., 2004; Dercon et al., 2005; Victora et al., 2008).

Risk aversion leads to under-investment and under-adoption of improved agricultural production technology. Farmers tend to use precautionary strategies to protect against the possibility of catastrophic loss in the event of a climatic shock and thus do not optimize management for average conditions, but for adverse conditions. These *ex-ante*, precautionary strategies include selection of less risky but less profitable crops and cultivars, shifting household labor to off-farm activities, and avoiding borrowing and investment in productive assets (including soil fertility) and improved production technology (Barrett et al., 2004; Dercon, 1996; Fafchamps, 2003; Kebede, 1992; Marra et al., 2003; Rose, 2001; Rosenzweig and Stark, 1989; Dercon and Christiaensen, 2011; Simtowe, 2006; Morris et al., 2007). Evidence from ICRISAT village studies in India and Burkina Faso shows that the resulting cost is much greater for those who are relatively poor within a poor farming community (Rosenzweig and Binswanger, 1993; Zimmerman and Carter, 2003). Risk aversion extends beyond farmers to institutions, impeding investment in rural areas and the development of agricultural value chains. Losses from covariant climatic or other shocks can exceed the reserves of an insurer or lender, and lead to financial market failures in many low-income countries (Besley, 1995; Miranda and Glauber, 1997; Poulton et al., 2006).

Climate-related risk contributes to rural poverty in three ways. First, *ex-ante* risk management strategies reduce the productivity and profitability of existing assets, and discourage accumulation of productive assets. Second, *ex-post* coping responses to severe or repeated climate shocks can force non-poor but vulnerable households to divest their productive assets. For some households this status will be transitory, others will fall or remain at a point below the poverty trap threshold. Third, the tendency for risk tolerance to decrease with decreasing resource endowment contributes to the higher opportunity cost of climate risk for the relatively poor (Carter and Barrett, 2006). Furthermore, with institutions or governments operating at an aggregate scale, climate risk can constrain economic opportunities and hence reinforce poverty and the potential for poverty traps at the household level (Barrett and Swallow, 2006; Carter and Barrett, 2006).

The agricultural research-for-development (AR4D) community has developed a number of agricultural production technologies and practices, such as stress-adapted crop germplasm, conservation agriculture and agroforestry systems, that aim to mitigate risk and foster resilience in the face of climate variability. Institutional interventions, such as index-based agricultural insurance and forms of social protection such as cash transfers, which have their origins largely outside of AR4D, seek to mitigate risk and build resilience through other mechanisms, and hence may play a complementary role to agricultural production technologies and practices. Understanding the mechanisms by which climate-related risk contributes to the extent and persistence of poverty provides a basis for assessing the potential for these risk management interventions to overcome the adverse impacts of risk, targeting interventions appropriately, hence, contributing to pathways out of rural poverty in high-risk environments.

The degree of impact from shocks will vary according to farmers' socio-economic status, given that the extent of asset and labor endowments affects capacity to smooth consumption in the face of shocks (Baulch and Hoddinott, 2000). Designing and targeting risk management interventions for effective poverty reduction therefore requires disaggregated understanding of 'the poor', facilitating understanding of poverty causes and dynamics (Hulme, 2003). A key distinction is between transitory and chronic poverty (Barrett, 2005). If people's assets - or related measure - fall below a poverty line but subsequently recover, then their poverty status is transitory. In contrast, when people have little or no mobility and experience poverty for extended periods, perhaps throughout their lives or between generations, poverty is chronic (Barrett, 2005). For people living in chronic poverty, risk and its impacts on farmer and institutional decision-making, contributes to conditions associated with poverty traps. A poverty trap occurs when households fall below a critical threshold of assets, below which individuals are unable to accumulate the necessary resources to escape poverty (Barrett, 2005; Carter and Barrett, 2006). People's poverty status, and whether this poverty is transitory or chronic, will affect their ability to take up agricultural production technologies and practices, and the extent to which institutional interventions for climate risk management will enhance this uptake. This raises the need for appropriate targeting to ensure that production technologies and practices, and complimentary institutional interventions, target the types of farmers best placed to pursue agricultural pathways out of poverty.

The literature that links climate-related risk to the extent and the persistence of rural poverty in these environments suggests a poverty reduction impact pathway that includes intermediary impacts of risk management interventions. The most direct impacts of these interventions are smoothed production, income and/or consumption across the range of climate variability; and protection of productive assets, including the health of household members, in the face of extreme climate events. Both of these impacts may alleviate risk-related barriers to adopting improved agricultural production technologies and practices, and accessing credit and market opportunities. Stabilized production, income and consumption; protection of human capital and productive assets during shocks; and the adoption of improved agricultural technologies and practices can all contribute to improved household food security and wealth. In time, the resulting cumulative improvement in household welfare, and investment of accumulated wealth in further farm and non-farm income generating activities, may move the household out of poverty. Consistent with this understanding of climate risk management impact pathways, this paper assesses evidence, published in the last ten years, that a set of risk-mitigating production technologies and institutional interventions contribute to poverty reduction through: (a) stabilizing production, income or consumption; (b) protecting productive assets in the face of shocks; (c) fostering uptake of credit and improved technologies; and (d) improving household welfare measures (income, food security, wealth). We discuss the state of the evidence from available impact studies, adoption and scaling issues, and the prospects for further exploiting the complementarities between the technological and the institutional risk management interventions included in this review. Finally, we discuss the roles that climate-risk management interventions can play in efforts to reduce rural poverty, and the need for further work to identify and target environments and farming populations where improved climate risk management could accelerate efforts to reduce rural poverty.

While past reviews have summarized the evidence for individual climate risk management interventions, this paper seeks to contribute to available knowledge by exploring the complementarities among technological and institutional climate risk management interventions through the lens of the identified poverty reduction impact pathway, and by incorporating a number of very recent evaluation studies. It is a contribution to a special issue, "Agricultural research for rural prosperity: Rethinking the pathways," that reviews the contribution of agricultural research-for-development to a set of pathways out of rural poverty.

2. Approach

We reviewed recent published evidence about a set of risk-reducing agricultural production technologies and practices and institutional interventions: (a) stress-adapted crop germplasm, (b) conservation agriculture and related agronomic practices, (c) diversification strategies including agroforestry, (d) index-based agricultural insurance, and (e) social protection (cash or in-kind transfers). These interventions were selected because they aim to reduce risk and foster resilience in smallholder agricultural systems in risk-prone marginal environments; and because they are targets of ongoing interest, investment and evaluation by the international agricultural research-for-development (AR4D) community. Our analysis of the evidence considered only studies published in English during the most recent decade (2007–2017), that: (a) address risk reduction impact pathways, (b) provide quantitative evidence based on primary analyses, and (c) are relevant to poverty in the developing world. Candidate publications were identified through a combination of authors' familiarity with evaluation literature in their areas of expertise, keyword searches with Google Scholar, and forward searches of publications that cited relevant evaluation studies. From the > 400 candidate publications that we reviewed, only 62 met our inclusion criteria. They are listed and summarized in Appendix 1.

Based on our understanding of the mechanisms by which climate-related risk contributes to rural poverty, we mapped the evidence from each of the studies that met inclusion criteria, onto five types of impact: (a) stabilized production or income; (b) protected assets in the face of shocks; (c) increased uptake of capital, production technologies and market opportunities; (d) improved livelihood and welfare measures (linked explicitly to risk reduction); and (e) reduced poverty. We identified the agricultural commodities involved, and the farming system(s) covered based on maps and criteria in Dixon et al. (2001). We summarize the numbers of studies reporting evidence on each of these types of impact, and made a subjective assessment of the strength of the evidence, for each risk management intervention (Table 1). We did not attempt to rate strength of evidence from individual studies. While all of the studies included in the review present empirical evidence, the quality of evidence presented is quite variable, ranging from stylized ex-ante modeling and analysis of statistical association, to rigorous randomized control trials (RCTs).

3. Risk-reducing production technologies

3.1. Stress-adapted germplasm

Following early major gains in productivity and poverty reduction from crop breeding in high-potential environments associated with the Green Revolution, research and breeding programs have increased attention to tolerance to climate-related stresses (Waddington et al., 2010), including major investment in drought-tolerant maize in sub-Saharan Africa (Cairns et al., 2013; Masuka et al., 2017a, b), and in breeding rice for tolerance to drought, flooding and salinity across regions (Collard et al., 2013; Ismail et al., 2013). Of the 12 studies on stress-tolerant germplasm included in our analysis (Appendix 1), six were multi-season experiment station or farm trials that documented stabilized and generally increased yields under varying climatic stress conditions, relative to control varieties (Birthal et al., 2012; Dar et al., 2013; Sarangi et al., 2016; Setimela et al., 2017a, b; Singh et al., 2009). Newer drought-tolerant maize cultivars consistently outperform commercial varieties under drought conditions in field trials (Masuka et al., 2017a, b; Setimela et al., 2017a, b). Greater documentation of yield gains is required, in stress and non-stress years, particularly under on-farm conditions. One on-farm study found that drought-tolerant maize did not outperform other improved maize varieties used in Malawi during the 2011/12 drought (Holden and Fisher, 2015a), although Setimela et al. (2017a, 2017b) characterized half of the drought-tolerant varieties cited in this study as old and non-drought tolerant. Evidence about the relative performance of drought-tolerant and standard commercial varieties under non-stressed conditions is mixed. On-farm trials reported by Setimela et al. (2017a) showed no yield penalty in climatically good years, but Holden and Fisher (2015b) found on-farm yields of stress tolerant maize to be lower than current modern varieties in climatically good years in Malawi (although these varieties were not classified as new nor drought tolerant by Setimela et al. (2017a, b). Drought and flood tolerant rice, which was developed using marker assisted selection to improve current mega-varieties, reportedly experienced no significant yield penalty under non-stress conditions (Ismail et al., 2013; Dar et al., 2013, 2017).

A few studies have estimated the actual or potential impacts of the substantial investment in breeding for climate-related stresses on farmers' livelihoods. For example, Birthal et al. (2012) attributed 33–46% of an income benefit from adopting drought-tolerant groundnut, to reduced yield variance. In a study in India, Emerick et al. (2016) attributed much (43%) of an observed income benefit from receiving randomly distributed stress-tolerant rice seed packets, to their positive influence on adoption of improved management practices and credit. Several ex-post assessments of livelihood benefits were excluded because they considered only a single year of data and hence provided no evidence of the role of risk reduction. Ex-ante estimates of the potential economic benefits to producers and consumers from existing or anticipated advances in stress-tolerant germplasm, based on economic equilibrium modeling, are quite high. For stress-tolerant maize, estimates ranged from US$362 to US$1535 million in targeted African countries over a 10-year period (2007–2016) (Kostandini et al., 2013; La Rovere et al., 2014). Mottaleb et al. (2012) estimated a US$2018 million benefit, over a 40-year period (2011–2050), for a stylized new drought-tolerant rice cultivar adopted across South Asia.

Table 1
Summary of published evidence of risk-related impacts of selected interventions, including numbers presenting evidence and subjective aggregate assessment of strength and consistency of evidence.

Risk management intervention	N	Stabilize production, consumption		Protect productive assets		Increase uptake of capital and technology		Improve livelihoods, welfare		Reduce poverty rate	
		N	Evidence	N	Evidence	N	Evidence	N	Evidence	N	Evidence
Stress-adapted germplasm	12	9	Strong	0	None	1	Weak	3	Moderate	0	None
Conservation agriculture	14	14	Mixed	0	None	0	None	2	Weak	0	None
Diversified farming systems[a]	12	6	Moderate	2	Weak	0	None	5	Moderate	0	None
Index-based agricultural insurance	24	0	None	6	Moderate	19	Strong	14	Moderate	2	Weak
Social protection	5	3	Moderate	0	Weak	1	Moderate	5	Strong	0	None
Total	62[b]	31		8		21		27		2	

[a] Diversified farming systems include agroforestry.

[b] The number of publications (60) is less than the number of cases (67) due to publications that evaluated more than one of the interventions.

3.2. Conservation agriculture practices

Conservation agriculture (CA) aims to sustainably improve and stabilize production, through a combination of reducing soil disturbance from tillage, maintaining soil cover with organic material, and crop diversification through intercropping or rotations. The practices that comprise CA vary (Andersson and D'Souza, 2014), and sometimes include additional soil fertility, water or weed management practices. Our review includes studies that evaluate all three components of CA, and a few studies that evaluate component practices and meet our inclusion criteria. The majority of CA publications reviewed did not assess risk-related impacts, and were therefore excluded from our analysis. All 14 of those included in our analyses include cases in which CA practices stabilized yields in the face of climate fluctuations. Yield and risk reduction benefits of CA have been attributed to improved water infiltration and retention, accumulation of soil C (Thierfelder and Wall, 2009, 2010; Palm et al., 2014; Powlson et al., 2016), and avoidance of heat stress through modification of the microclimate due to the presence of organic residues (Sapkota et al., 2015). These benefits generally increase over time, and may not be realized in the first few years (Jat et al., 2014; Thierfelder et al., 2015).

Only three of the 14 studies included in our analysis went beyond biological response to assess livelihood impacts, employing enterprise budget analysis to characterize farm-level cost and income (Magnan et al., 2011; Michler et al., 2016; Mupangwa et al., 2017). We did not find assessments, published during the most recent decade, of how the risk reduction benefits of CA impact poverty rates or other measures of farm household wellbeing. Econometric analysis of a survey of 1623 farm households showed that adoption of CA significantly improved food security status in Mozambique, but not in Malawi or Mozambique (Mango et al., 2017). However, the study did not consider the role of risk reduction.

Some studies (Gatere et al., 2013; Branca et al., 2013), including a recent meta-regression across many sites and publications (Steward et al., 2018), indicate that CA shows greater risk management and productivity benefits in more drought-prone environments. But several studies based on networks of field (farm or experiment station) trials across environmental gradients, and meta-analyses across studies, paint a more complex picture. For example, in a 3-season networks of farm trials across Zimbabwe, direct seeding was the most effective land preparation system for stabilizing and increasing maize yields in medium-rainfall agroecological zones, but basins were more effective in low-rainfall zones (Mupangwa et al., 2017). CA improved wheat yields more in an extreme rainfall year than in a normal season (16% yield advantage vs. 8% in a normal year) in NW India (Aryal et al., 2016), but increased yield loss from waterlogging under excessive rainfall conditions in southern Africa (Rusinamhodzi et al., 2011; Gatere et al., 2013; Thierfelder and Wall, 2012). This context dependency of the benefits of CA is consistent with reviews (Thierfelder et al., 2017; Baudron et al., 2015), and is not surprising given the range of agro-ecologies studied and the heterogeneity of practices comprising CA. Highly variable adoption rates and significant dis-adoption of conservation agriculture in sub-Saharan Africa (Knowler and Bradshaw, 2007; Baudron et al., 2012; Andersson and D'Souza, 2014) are attributed to competing demands for resources (e.g. using residues as soil cover or livestock feed, Valbuena et al., 2015), the time lag between practice adoption and realization of benefits (Thierfelder et al., 2017), and complexity of the practice (Gatere et al., 2013; Thierfelder et al., 2015).

3.3. Diversified farming systems

Diversification of varieties, crops, farm activities or income streams is a widely recognized risk management strategy. The potential to stabilize farm income through diversification is a function of the proportion of mean income contributed by each activity, and the variance-covariance matrix of income the set of activities; the less positive the co-variability among the different activities, the greater the scope for reducing overall risk through diversification. On-farm diversification may be achieved through crop diversification, integration of crops and livestock, or integration of trees into crop and/or livestock systems (i.e., agroforestry). Our analysis considered 12 studies of risk management benefits of diversified farming systems: 5 on crop or cultivar diversification, 1 on livestock, and 6 on agroforestry systems. Our analysis excluded the significant body of literature that deals with diversification between farm and non-farm income sources.

While increasing the number of crop species does little to mitigate climate risk if the crops respond similarly to climate stresses (Barrett et al., 2001), diversifying crops of different functional types, or with differing phenology, may substantially reduce risk (Gilbert and Holbrook, 2011). Matsuda (2013) found the local crop diversification strategy in an upland farming system in central Myanmar to be effective at stabilizing production and income in the face of high interannual rainfall variability, because yields of the main crops (pigeon peas, cotton, and sesame) are weakly correlated. Nalley and Barkley (2010) show that growing portfolios of different wheat varieties in the Yaqui Valley of Mexico, with differing phenology and stress response, could reduce production variance by up to 33% while holding yields constant, or increase mean yields by 1–2% holding variance constant. Extrapolating to similar wheat environments globally, they suggested optimal cultivar diversification could increase total wheat production revenue by US$ 32–73 million without increasing risk.

Synergistic interactions between system components often provide additional productivity or risk reduction benefits. For example, cultivar blends can reduce disease incidence (Barot et al., 2017). Crop diversification is one of the pillars of CA (Section 3.2), and two of the studies documented cereal yield stabilization from crop diversification in the context of CA (Kassie et al., 2015; Arslan et al., 2015).

In the one study we found that presents relevant evidence on risk-related benefits of livestock diversification, Megersa et al. (2014) showed that Borana pastoralist households in southern Ethiopia, who practiced herd diversification, had fewer months of food deficit and lower household food insecurity.

Agroforestry further diversifies crop, livestock, and mixed crop/livestock systems by integrating trees into the production system. By varying the tree species (e.g. fertilizer trees, fruit trees, fodder shrubs, native species) and the spatial arrangement of trees (e.g. rows and alleys, shelterbelts, natural regeneration), hundreds of permutations of agroforestry have been developed to achieve diverse outcomes (e.g. diversified production, improved soil health, reduced erosion) (Kim et al., 2016; Reed et al., 2017). The benefits of agroforestry vary considerably across locations, in response to biophysical and socio-economic factors such as farmers' landholdings (Quinion et al., 2010), how the system is managed (Steffan-Dewenter et al., 2007), and economic (dis-)incentives to manage common resources sustainably (Faße and Grote, 2013).

The six included studies on diversification through agroforestry showed a range of benefits. Agroforestry stabilized cereal yields in the face of climate variability in two studies (Sileshi et al., 2011, 2012), although Sileshi et al. (2011) found this impact in a Nigeria site but not in a Zambia site. Agroforestry also reduced the negative impact of climate shocks by reducing the use of negative coping strategies during drought in Kenya (Thorlakson and Neufeldt, 2012), and by reducing recovery time from drought, flooding and storms in Vietnam (Simelton et al., 2015). Three studies provide evidence of a positive relationship between agroforestry adoption and household food security (Bostedt et al., 2016; Ickowitz et al., 2014; Thorlakson and Neufeldt, 2012). It is unknown whether the risk reduction benefits of agroforestry, demonstrated in a few contexts, is a transmutable feature across all agroforestry systems due to the limited number and diversity of long-term agroforestry trials.

4. Risk-mitigating institutional interventions

While the AR4D community has responded to the shifting emphasis on marginal environments, and growing awareness of the connection between poverty and risk in these environments, much of the recent emphasis has been on technology solutions. However, the limitations of these technologies suggest that further measures are needed to facilitate greater use of productivity-enhancing agricultural technologies and practices, while mitigating the risks that cannot be managed through farm production technologies alone. Several institutional interventions that have their origins largely outside of agricultural research, aim to mitigate climate-related risk and build resilience through mechanisms other than affecting on-farm productivity, and may therefore play a complementary role. We review the body of available recent evidence for index-based agricultural insurance, and then also briefly discuss the contribution of particular forms of social protection to efforts foster climate resilience and reduce rural poverty.

4.1. Index-based agricultural insurance

Index-based insurance is a recent innovation (since the mid-1990s) that triggers payouts based on an index (e.g., rainfall, vegetation remote sensing, area-average yield) that is correlated with agricultural losses, rather than actual losses. Index insurance has largely overcome the obstacles of moral hazard, adverse selection, high transaction costs and payout delays that made traditional loss-based crop insurance infeasible for smallholders. However, it introduces basis risk – resulting from the imperfect relationship between farmers' losses, and the index that triggers payouts – as a new challenge. It has contributed to a resurgence of interest in agricultural insurance in the developing world, especially in the context of climate change adaptation, and contributions to several of the Sustainable Development Goals (GIZ, 2017). Index insurance programs aim to achieve both livelihood protection (preserving productive assets and hastening recovery after shocks) and/or livelihood promotion (supporting access to credit, and adoption of improved farm technologies and practices) goals.

Index-based livestock insurance programs are designed primarily to protect herders' main productive asset in the event of major shocks. Payouts following a major winter weather disaster in Mongolia improved herd recovery by reducing distress sales and slaughtering of animals, and reducing credit constraints (Bertram-Huemmer and Kraehnert, 2015). In northern Kenya, payouts following a severe drought reduced distress livestock sales among relatively well-off pastoralists. For poorer households with assets below an empirically determined poverty trap threshold, insurance protected the human capital of the next generation by reducing coping through rationing food intake – following the payout (by 43%), and even before the payout (by 30%) (Janzen and Carter, 2013).

The most commonly reported benefits of index insurance (19 of the 24 studies analyzed) involved increased adoption of more profitable production technologies and practices (Table 1). This was demonstrated in evaluations of operational programs in Ethiopia (Madajewicz et al., 2013), Burkina Faso (Stoeffler et al., 2016) and Mexico (Fuchs and Wolff, 2016; De Janvry et al., 2016); and in experimental studies in a range of settings (Hill et al., 2017; Karlan et al., 2014; Cole et al., 2017; Miura and Sakurai, 2015; Delavallade et al., 2015; Ward et al., 2015). In several cases, adoption of improved technologies was enabled by enhanced access to credit. The positive relationship between index insurance and adoption of improved production technology is however not expected to be universal. Carter et al. (2016) argued that index-based insurance can be expected to significantly stimulate adoption of technology only in environments where risk is high and farmers lack collateral to secure loans. In an experimental setting in Cambodia, insurance stimulated technology adoption only for the relatively wealthy farmers, and only when the probability of a shock was known (Falco et al., 2016).

A subset of the studies that demonstrate positive impacts of insurance on uptake of improved technologies and practices also found evidence of positive impacts on crop production (Fuchs and Wolff, 2016; Delavallade et al., 2015), wealth accumulation (Madajewicz et al., 2013) and household food security (De Nicola, 2015; Janzen and Carter, 2013; Isaboke et al., 2016). In a pastoral system in northern Kenya, where prior research (Janzen and Carter, 2013) established the existence of nonlinear herd dynamics associated with a poverty trap, Cissé and Ikegami (2016) assessed the impact of index-based livestock insurance on household resilience expressed as the future probability of two well-being indicators (herd size and child health). Holding an insurance contract increased the probability of next-season herd size remaining above a 16 TLU[1] estimated poverty trap threshold, in both drought and non-drought years; and significantly decreased the probability that children would be severely malnourished during a drought year.

Concerns about weak demand in many index-based insurance initiatives and randomized trials (Giné et al., 2008; Cole et al., 2017; Binswanger-Mkhize, 2012; Tadesse et al., 2015) are balanced by recognition that several initiatives that target smallholder farmers have scaled up rapidly in recent years (Greatrex et al., 2015). Consistent with evidence that farmer demand is influenced by design-related factors such as the degree of basis risk and farmers' level of understanding and trust (Hill and Viceisza, 2012; Karlan et al., 2014; Cai et al., 2011; Elabed and Carter, 2015), Greatrex et al. argue that the prospects for scaling up index insurance for smallholder farmers may be determined largely by evolving capacity to overcome the challenges and provide effective services. Likewise, Carter et al. (2017) expands on options for overcoming constraints to farmer uptake. Developing the capacity of private insurers to address farmers' insurance needs at scale may continue to depend on public support including: creating an enabling regulatory environment, investing in meteorological and agricultural data systems, educating farmers about the value of insurance, and facilitating international reinsurance. Time-bound smart subsidies may be needed to overcome initial setup, first mover, or other market failure problems that can arise when an insurance market is first emerging may be justified.

4.2. Social protection

Social protection programs aim to protect chronically poor households through social assistance (cash or in-kind transfers), social insurance (cover against designated contingencies), or labor market programs (e.g. unemployment benefits) (FAO, 2015). Evidence is emerging that by alleviating credit, savings and liquidity constraints, such transfers can stimulate agricultural production through investment in technology and productive assets (farm, livestock, non-farm), and increased own-farm household labor allocation (Asfaw et al., 2014; Davis et al., 2016; Fisher et al., 2017a, 2017b; Gertler et al., 2012; Tirivayi et al., 2016; Todd et al., 2010; Kabeer et al., 2012; Hagen-Zanker et al., 2011). Positive impact on savings and reduction of pressure on informal insurance mechanisms is also noted (Bastagli et al., 2016; Davis et al., 2016). The literature stresses generally weak existing linkages between social protection and agricultural interventions, or tensions where linkages are present (Arnall et al., 2010; Davies et al., 2008, 2009; Devereux and Guenther, 2009). The role conditionality (i.e. requiring households to meet conditions for transfers) plays in delivering impact is debated (Pellerano and Barca, 2014).

Systematic evidence on the nexus between climate risk, social protection, poverty and agriculture is only recently emerging, in response to a conceptual shift toward consideration of how social protection can foster resilience. Only a small subset (5) of the available evaluation studies on social protection attribute livelihood benefits to climate risk

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[1] One Tropical Livestock Unity (TLU) = 1 cow, 0.7 camel, 10 sheep or 10 goats.

reduction (Appendix 1). Through their mitigating effect on climate shocks, well-designed social protection programs that enable household to cope with agricultural and price shocks reduce the need for costly risk avoidance strategies, as Asfaw et al. (2017) and Lawlor et al. (2017) demonstrate for the Zambia Child Grant Program. Jensen et al. (2014) found that social protection contributed resilience to climate shocks among Kenyan pastoralists, but found index-based insurance to have similar effect at lower cost. In Nicaragua, Macours et al. (2012) found that integrating vocational training or productive investment grants improved the effectiveness of cash transfers at mitigating the impacts of drought. Recent cross-country synthesis from Sub-Saharan Africa found that cash transfers reduce the impact of weather shocks, especially for the poorest households (Asfaw and Davis, 2018).

Motivated in part by climate change, adaptive social protection emphasizes livelihood promotion in addition to protection, and mechanisms to scale up (through increased benefits per participant) and out (to an expanded set of beneficiaries) in the face of emerging shocks (Arnall et al., 2010; Davies et al., 2008, 2009, 2013). Innovations in risk finance aim to increase the effectiveness and timeliness of adaptive social protection programs in the face of climatic risks. For example, Ethiopia's Livelihoods Early Assessment and Protection (LEAP) program adds a layer of contingent finance to the government's Productive Safety Net Program (PSNP), using climate-informed water balance information and parametric triggers to trigger release of funds to quickly scale up PSNP interventions in the face of drought (Drechsler and Soer, 2016; Soares et al., 2016; Kuriakose et al., 2012). Forecast-based finance programs, being developed and piloted by Red Cross and by WFP's FoodSECuRE (Food Security Climate Resilience Facility) initiative, aim to exploit climate prediction and early warning systems to increase the lead-time of funds available to countries and communities facing anticipated climate shocks (Coughlan de Perez et al., 2015, 2016; Coffey et al., 2015). Innovative delivery mechanisms for social protection benefits, such as conditional Early Recovery Vouchers, reduce some of the moral hazard and perverse incentives associated with existing adaptive social protection benefits (Hess and Hazell, 2016).

5. Discussion

5.1. How effective are climate risk management options at reducing poverty?

Our analysis of recent evidence about the effectiveness of technological options for managing climate risk in smallholder agriculture suggests several generalizations. First, most of the evaluations we reviewed reported cases where production variability was reduced. Reduced variability was generally treated as a secondary benefit to increases in mean productivity. Second, evidence about how reductions in production risk impact farmer livelihoods or poverty rates is scarce. Third, multi-site studies show that the risk benefits of the natural resource management technologies (conservation agriculture and related practices, diversified production systems including agroforestry) are context-specific; they do not show benefits in all agroecological environments, or for all farmers in a given environment.

The nature and amount of published evidence that our review considered varied between the two types of institutional risk management interventions that we considered. In the case of index insurance, the impacts that have been reported have been consistent with the objectives of the insurance initiatives. The few available studies of the livelihood protection role of insurance payouts, in the face of major climate shocks, focused on livestock insurance initiatives that were designed to protect against herd loss. A growing body of recent evidence, focused on index insurance for livelihood promotion, demonstrates its effectiveness at overcoming risk-related barriers to adoption of more profitable production technologies and practices across contexts, but evidence of how this impacts production, income and poverty rates is sparse.

We found substantial evidence that the climate risk management interventions that we reviewed are effective at stabilizing farm production and income, mitigating the impacts of extreme events on farm households and their assets, and enabling more productive farming practices by removing risk-related adoption barriers; and modest evidence of resulting improvements in measures of farm household well-being. However, we found little empirical evidence that these benefits have led to significant numbers of farmers exiting either transitory or chronic poverty.

The gaps in evidence reflect the limitations of the evaluation studies that have been conducted, and not just the effectiveness of the interventions. Time lags between development of new innovations and demonstrable impacts on poverty rates affect the available evidence for index-based agricultural insurance and innovations in adaptive social protection supported by contingent finance mechanisms. Economic equilibrium modeling studies are useful for ex-ante estimation of the aggregate impacts of innovations on producer and consumer well-being and poverty rates, yet they usually consider only average response (i.e., average shifts in supply curves). A few such studies recommended extending analyses to include risk mitigation benefits (Alene et al., 2009; Kassie et al., 2017). Even for production technologies that explicitly aim to mitigate climate-related risk, most ex-post studies do not use data from enough seasons to capture interactions between management and climate variability, and hence assess risk mitigation benefits. In part, this is due to short project cycles, and to donor reluctance to support continued monitoring and evaluation after the end of a project. While multi-site studies can sample weather variability in space, attributing response to weather fluctuations it is difficult because of confounding factors such as soil properties and the socioeconomic environment.

Disappointing farmer adoption of the technologies and practices reviewed here appears to be one factor that has limited their contribution to food security, climate resilience and poverty reduction goals (Adesina and Chianu, 2002; Conteh et al., 2016; Deressa et al., 2009; Marenya and Barrett, 2007). Complex interacting factors contribute to adoption and scaling challenges. For example, natural resource management practices such as conservation agriculture and agroforestry are knowledge-intensive (Kassam et al., 2009), but deep cuts to publicly funded extension services in the developing world have reduced farmers' access to training and expert guidance on these technologies (Hellin, 2012). Rural labor shortages at key times in the agricultural calendar, sometimes driven by competing on-farm and off-farm income generating activities, can constrain adoption of labor-intensive technologies such as conservation agriculture particularly for farmers who cannot afford labor-saving inputs such as herbicides (Giller et al., 2009). Stress-tolerant seed is less knowledge- and labor-intensive than the natural resource management practices reviewed, which seems to make it easier to scale (Senyolo et al., 2017). A significant body of research (introduced briefly in Section 1) points to climate-related risk and its impacts on farmer and institutional behavior as a key obstacle to the adoption of improved production technologies, including the risk-reducing technologies included in our review, in risk-prone marginal regions.

5.2. Complementarity of technological and institutional risk management options

Institutional risk management options complement risk-reducing production technologies in at least two ways. First, they intervene in different aspects of the risk-poverty connection. The most-reported benefits of the technologies reviewed involve reducing production or income losses when weather-related stresses occur; whereas the most frequently reported benefits of index insurance involve increased access to capital and uptake of improved production technologies and practices, reducing the opportunity cost associated with risk-averse farmers' precautionary ex-ante strategies (Table 1). For risk-prone environments

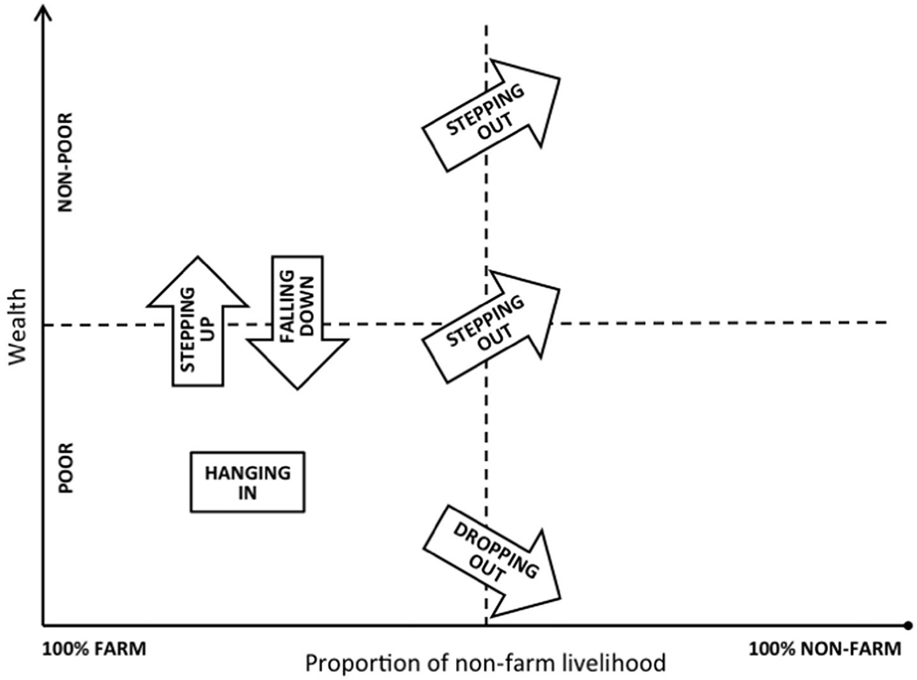

Fig. 1. Potential livelihood pathways for smallholder farmers.

where rural poverty is pervasive, this suggests that insurance can be used effectively to increasingly overcome risk-related barriers to adoption of production technologies and practices that mitigate downside risk. For those living in chronic poverty in rural areas, for whom a poverty trap can be most pernicious, adaptive social protection can provide a complementary safety net to reduce climate-risk.

The second form of complementarity involves "risk layering." When appropriately targeted, the technologies reviewed (stress-tolerant germplasm, conservation agriculture practices, diversified farming systems) stabilize production in the face of moderate climate fluctuations, and help guard against transitory poverty, but are not able to buffer the impacts of extreme events such as severe drought (Carter et al., 2017). Index insurance can be designed to trigger payouts for any level of climatic stress. But to be affordable, it should target severe shocks that occur relatively infrequently. This form of complementarity between insurance and drought-tolerant seed is supported by a stylized analysis informed by data from Ecuador (Lybbert and Carter, 2015), and by evidence of demand for bundled drought-tolerant seed and insurance in India and Bangladesh (Ward and Makhija, 2016; Ward et al., 2015).

5.3. *Targeting climate risk management to farm livelihood pathways*

It is important to ensure that climate risk management approaches and agricultural production technologies are targeted appropriately, based on an understanding of farming households' socio-economic and relevant poverty status, linked to the diversity of livelihood strategies and potential pathways out of poverty. The livelihood strategies available to a given household will depend on household asset and labor endowment (Carter and Barrett, 2006). From an asset-based poverty perspective, the interaction between available assets (land, financial, social, human, etc.), and the physical, policy, economic and institutional environment that frames opportunities for household risk management and vulnerability reduction will determine different livelihood strategies.

A simple typology of farmer livelihood pathways (Dorward, 2009; Dorward et al., 2009; DFID, 2015; Dixon et al., 2001) can focus thinking about what roles particular CRM interventions can play, for particular types of households, in rural poverty reduction. First, "*stepping up*" describes the process of escaping poverty through changes to their current farming activities. The main pathways for *stepping up* are extensification (i.e., cultivating more land or increasing herd size), intensification (i.e., producing more of existing commodities per unit of land, e.g., through the use of production enhancing agricultural technologies), diversification, or commercialization[2] (i.e., shifting to higher-value market-oriented production) of farm-based livelihoods (Dixon et al., 2001). Second, "*stepping out*" describes the process of escaping poverty by increasing income and assets through non-farm livelihood sources. For "*stepping out*" farm households, assets that are accumulated through farming or through social protection asset transfers are invested to increase off-farm income opportunities or an exit from agriculture, although globally most smallholder farm households already derive part of their income from non-farm activities. Third, "*hanging in*" describes the situation for farmers who are trapped in poverty, who seek to preserve their current meager levels of welfare and assets in the face of stresses and shocks. A key challenge for agricultural research and development is to intervene through technology, policy or services in ways that enable farmers to move from *hanging in*, to *stepping up* or *stepping out*. We add two more pathways, recognizing that, in the face of climatic and other risks, shocks can reverse the pathways out of poverty, compounding otherwise transitory poverty. Thus, farmers who are "*stepping up*" may "*fall down*" into increasing poverty, and farmers who are "*hanging in*" may "*drop out*" of farming into a deeper and more intractable state of destitution (Mushongah and Scoones, 2012; Barrett and Constas, 2014). For those both "*hanging in*" and "*dropping out*", poverty is endemic and is associated with a poverty trap. In these cases, agricultural production per se, even when complemented by institutional interventions, may not be a realistic path out of poverty. Instead, a more appropriate intervention may be social protection until the extreme poor are either able to build up sufficient assets and eventually move out of poverty via agricultural livelihood pathways (i.e. *stepping up*) or until growth in non-agricultural sectors create sufficient accessible job opportunities (i.e. *stepping out*).

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[2] Although Dixon et al. (2001) did not list *commercialization* as a pathway out of poverty, their treatment of *diversification* includes shifting to higher-value, market-oriented production.

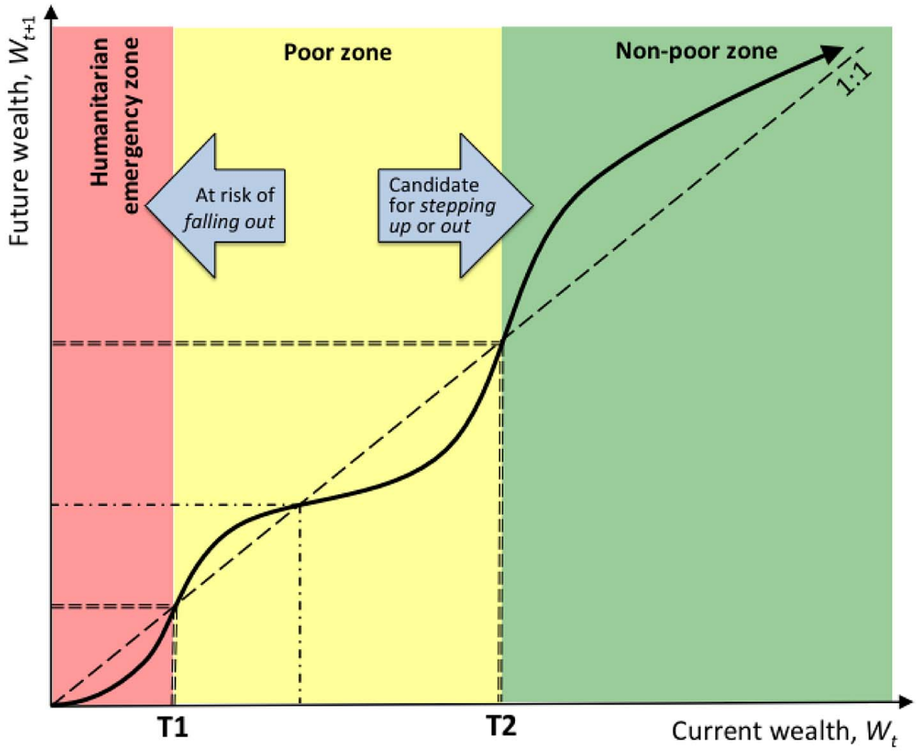

Fig. 2. Conditional wealth expectation function for a stylized farm household, in the presence of poverty traps. Adapted from Barrett et al. (2007).

Fig. 1 illustrates these potential livelihood pathways, along axes of wealth and dependence on farm vs. non-farm livelihood sources.

While transitory movements between poor and non-poor states can cause stress without necessarily affecting a household's long-term livelihood trajectory, the thresholds and bifurcations associated with poverty traps, where present, can make the process of *stepping up* much more challenging, and the risk of *falling down* or *dropping out* much more costly to farmer livelihoods and poverty reduction efforts. This impacts on where agricultural development efforts are best targeted. In line with Dorward's (2009) livelihood pathways, Barrett et al. (2007) proposed a typology for targeting resilience-building rural development interventions in the context of risk and poverty traps. For a stylized household facing nonlinear wealth dynamics and poverty traps, Fig. 2 (adapted from Barrett et al., 2007; and Barrett and Constas, 2014) shows expected wealth in a future period (W_{t+1}) conditioned on current wealth (W_t). The household has the opportunity to accumulate wealth where this conditional expectation function falls above the 1:1 line, but will lose wealth with time where it falls below the 1:1 line.

The conditional wealth expectation function depicted in Fig. 2 bifurcates around two non-stable equilibria, or "tipping points:" T1 and T2. The space to the left of T2 represents a poverty trap, since it falls below a standard poverty threshold (P). The lower threshold, T1, recognizes that the some of the extreme poor (i.e., some of those *hanging in*) are vulnerable to falling irreversibly below a second threshold (T1) into destitution, physical impairment or ultimately death i.e. dropping out. Building on Barrett and Constas (2014) we refer to the stable equilibria between these thresholds as "non-poor," "poor" and "destitute" zones. This conditional wealth expectation function is stochastic, as climate and other stochastic drivers influence future wealth in response to farmers' decisions current resource endowment.

Building on Barrett et al. (2007), we highlight four intervention points for improving farmers' wellbeing in the face of climatic risk. First, "productive safety net" interventions that aim to firstly protect the vulnerable non-poor from *falling down* into the poverty zone in the face of a shock. Second, production technologies complemented by improved climate risk management, or "cargo nets" (Barrett, 2005) aim to enable some types of farmers in the poor zone to escape poverty and move to the right of T2 (i.e., *stepping up*). The third category is layered safety net interventions designed to protect the poor (or "*hanging in*" farmers) from *dropping out* into destitution by moving to the left of T1. For these farmers, production technologies are unlikely to be adequate; social protection is needed until they are either able to build up sufficient assets to *step up* out of poverty (as per the transitory poor), or until growth in non-agricultural sectors create sufficient accessible job opportunities to allow *stepping out*. Finally, those who have moved to the left of T1 (i.e. *dropping out*) will require emergency humanitarian relief that goes well beyond agricultural interventions or social protection.

Climate risk management plays a key role for overcoming risk-related barriers (e.g., farmers' risk aversion, risk aversion of lenders, or risk aversion impeding market/value chain development) to more profitable agriculture, for those in the poor zone but with the potential to transition to the right of T2. There is a growing body of evidence that index-based insurance catalyzes intensification, and sometimes commercialization, by reducing risk-related barriers to credit access and uptake of more profitable production practices. Although risk-reducing production technologies should, in principle, also prompt increased uptake of production inputs and more intensive production, we found evidence of this effect in only one study of the impacts of stress-tolerant germplasm (Emerick et al., 2016).

Improved climate risk management should in principle contribute to commercialization by encouraging investment in agricultural markets and value chains, by improving the reliability of smallholder farmers as suppliers, and by improving their access to the capital and technology needed that high-value commodities require. However, evidence is still lacking about the scope for improved risk management to fostering commercialization. Because rural livelihoods are embedded in a wider socio-economic context, opportunities to escape poverty by 'stepping out' into prosperous non-farm livelihoods must be linked to expansion of the non-farm economy and connectivity to markets (DfID, 2015).

Where those populations who are *hanging in* are highly vulnerable to the impacts of climate shocks, social protection (Section 4.2) play an important role in protecting them from *dropping out* into a state of destitution that would jeopardize the feasibility of future poverty reduction efforts. In addition to preventing *dropping out*, there is evidence

Table 2
Range of net returns (US\$ ha^{-1} $season^{-1}$) for categories of production-enhancing technologies, summarized from Harris and Orr (2014).

Technology	Conventional			Improved			N
	Min	**Median**	**Max**	**Min**	**Median**	**Max**	
Tillage (including conservation agriculture and residue retention)	0	118	587	121	289	4115	13
Rotations, fallows, intercropping	− 127	270	657	132	598	2134	16
Fertilizers and soil amendments	− 55	282	1084	178	760	1796	25
Pest and disease control	− 147	− 14	590	205	487	1129	6
Improved varieties	− 110	403	590	50	803	1021	5

that suggests that well targeted cash transfers, particularly in combination with agricultural interventions or vocational training, contribute to *stepping up* through their positive impact on farm productivity and to *stepping out* by overcoming barriers to profitable non-farm livelihood opportunities (Macours et al., 2012; Soares et al., 2016; Tirivayi et al., 2016; Fisher et al., 2017a, 2017b).

In risk-prone environments, *stepping up* can be a precarious process. In the presence of a poverty trap, ground lost from a shock cannot be regained quickly without costly intervention. For vulnerable non-poor and transitory poor, index-based insurance can play a productive safety net role, protecting productive assets and preventing falling down into a poverty trap in the face of an extreme climate event or other adverse shock. This role has been studied particularly in the case of index-based livestock insurance (Chantarat et al., 2017; Cissé and Ikegami, 2016).

From the perspective of targeting climate risk management for rural poverty reduction, a crucial question is, under what circumstances can risk-reducing technologies and institutional interventions enable farmers who are *hanging in* to *step up* into secure non-poor agricultural or *step out* into secure non-agricultural livelihoods (i.e. move to the right of T2 in Fig. 2)? Climatic and other risks (Section 1) can interact with other constraints to trap smallholder farm households in chronic poverty (poverty i.e. the zone between T1 and T2). From a review of farm survey data across 9 countries in SSA plus India, and published comparisons of net returns from 64 cases of improved vs. baseline farm production technologies, Harris and Orr (2014) argue that crop production could be a pathway out of poverty where smallholders are able to increase farm size, or where markets stimulate crop diversification, commercialization and increased farm profitability; but that for many, land and market access are too constraining for crop production alone to provide a feasible pathway out of poverty. The technologies that Harris and Orr based considered (summarized in Table 2) focus on intensification primarily of staple cereal crops, and excluded shifts to higher-value production (i.e., commercialization).

As their implementation continues to improve and scale up, the technological and institutional climate risk management innovations reviewed can be expected to contribute significantly to rural poverty reduction where two conditions are met: (a) household land and labor endowments, available technologies, supply chains and markets are sufficient to allow for stepping up through intensification and/or commercialization; but (2) climate-related risk currently excludes poor farmers from accessing available technologies, credit and market opportunities. As a step toward identifying where these conditions might hold at a very aggregate level, prior work identified major farming systems that are constrained by risk (Dixon et al., 2001). However, more research is needed to predict the contexts under which climate risk management can enable exit from poverty, in order to effectively target investment in these interventions.

6. Conclusions

A body of evidence links climate-related risk to the extent and the persistence of rural poverty in marginal environments. The AR4D community has responded to the shifting emphasis on marginal environments, and growing awareness of the connection between poverty and risk in these environments, but much of the emphasis is on the development and promotion of agricultural production technologies and practices. The production technologies and practices reviewed here demonstrate risk-reduction benefits primarily in the form of stabilizing stabilizing production and incomes. Evidence about how risk benefits translate to improved farmer livelihoods is scarce. Risk reduction and resilience benefits that these technologies are intended to provide are not universal, but depend on context-specific bio-physical (e.g., soil, climate) and socio-economic (e.g., access to markets, land and labor endowment) factors.

Several institutional interventions play a complementary role to the agricultural production technologies and practices in two ways. First, insurance and some social protection programs can be used to increasingly overcome risk-related barriers to adoption of more profitable production technologies and practices. Second, bundling risk-reducing technologies with insurance allows insurance to cover residual risks from severe shocks that technologies alone are unable to handle, while the technologies reduce the amount of risk that insurance must cover, thereby reducing its cost.

Given the heterogeneity of smallholder agriculture, and evidence of the effectiveness of the technological and institutional interventions reviewed, it is paramount to target these interventions where they are expected to be most effective. It is useful to think of three distinct roles that climate risk management plays in efforts to reduce rural poverty: (a) enabling ‘stepping up’ where climate-related risk is an entry barrier; (b) preventing the vulnerable non-poor from ‘falling down’ in the face of a climate shock; and (c) protecting those who are ‘hanging in’ from ‘dropping out’ into deeper poverty or destitution, in a way that reduces future options to enable them to step up to secure and prosperous farming or to step out of agriculture.

A few rapid changes in the world are likely to change the extent of rural poverty, and the opportunities available for smallholder farmers to escape poverty in risk-prone marginal environments. On the positive side, we note rapid expansion in investment in climate risk management through climate adaptation funding, a major global push on index-based insurance, and in some contexts, rapid development of agricultural value chains and expansion of market access. On the negative side, population growth in many rural areas is reducing average farm size, and climate change is intensifying risk from extreme events.

This review highlights significant gaps in evidence about the effectiveness of interventions that aim to build the resilience of smallholder farmers to climate-related risks. Effective targeting of these interventions also requires further research to identify the contexts under which particular climate risk management innovations, alone or in combination, can feasibly contribute to pathways out of poverty for smallholder farmers.

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Appendix 1. Selected evaluation studies of climate risk management interventions

Location	Farming system	Commodity	Intervention[a]	Impact[b]					Key finding	Reference	Method
				S	P	U	L	E			
Kenya	Maize mixed, Pastoral	Livestock	AF				+		Improved household nutrition.	Bostedt et al., 2016	Tree cover - diet quality correlation
Africa (21 countries)	Various	N/A	AF				+		Positive relationship between nutrition diversity and quality, and tree cover up to 45%.	Ickowitz et al., 2014	Regression of tree cover and Demographic Health Survey data
Zambia, Nigeria	Maize mixed (Zambia); Cereal-root crop mixed (Nigeria)	Maize	AF	±					Improved maize yield stability in Nigeria site, but not Zambia sites. In Nigeria, fertilizer + AF further stabilized yields.	Sileshi et al., 2011	Long-term (11–12-year) field trials
Zambia, Malawi	Cereal root crop mixed; maize mixed	Maize	AF	+					Increased stability of maize yields relative to fertilized maize monoculture.	Sileshi et al., 2012	Long-term (13-year) field trials
Vietnam	Lowland rice; upland intensive mixed	Various	AF		±				Reduced recovery time after drought, flooding, storms; but increased recovery time after cold spells.	Simelton et al., 2015	Adopter - non-adopter comparison based on survey, focus groups
Kenya	Maize mixed	Maize	AF		+		+		Increased average income and livestock holding. Reduced coping through borrowing, seed consumption, hiring out in flood and drought years. Mixed influence on meal rationing and distress livestock sales.	Thorlakson and Neufeldt, 2012	Matched samples from survey data; interviews, focus groups, field observations
India (Haryana)	Rice-Wheat	Wheat	CA	+					Yield benefit from adoption was greater in an excess rainfall than a “normal” year.	Aryal et al., 2016	2-year farm data, comparing adaptors and non-adaptors
Brazil (Paraná)		Soybean, maize, wheat,	CA	+					No-till and conservation tillage stabilized and increased soybean yields, increased mean wheat and maize yield. CA impacts increased with time.	Franchini et al., 2012	Long-term (23-year) field trial
Kenya	Maize mixed	Maize	CA	+					Tied ridges (most effective at semi-arid site) and mulching (most effective at sub-humid site) stabilized and increased mean yields.	Kiboi et al., 2017	Farm trials (4 seasons), interviews
Morocco	Highland mixed; rainfed mixed; dryland mixed; pastoral	Wheat	CA	+					By delaying expenditures, no-till allowed cost savings when emerging drought was apparent, increasing and stabilizing net income.	Magnan et al., 2011	Ex-ante, calibrated optimization model simulated with historic rainfall
Zimbabwe	Maize mixed; agro-pastoral millet-sorghum	Maize, sorghum, millet, groundnut, cowpea	CA	+					Increased yields in low and high rainfall years. Average returns can increase or decrease depending on crop.	Michler et al., 2016	Econometric, plot-level panel data (4-year)

Zimbabwe	Agro-Pastoral millet/ sorghum	Maize, cowpea, sorghum	CA	±		Mulching increased maize yield in low rainfall seasons. Factors confounded positive cowpea response to ripper in low rainfall season.	Mupangwa et al., 2012	Field trial (4 seasons)
Zimbabwe	Maize mixed; agro-pastoral millet/ sorghum	Maize, cowpea, soybean	CA	±		Direct seeding provided most stable maize yields in medium rainfall AEZ, and basins in low rainfall AEZ. Gross margin of CA treatments showed stochastic dominance, in medium and low rainfall AEZ, but conventional tillage showed stochastic dominance in high rainfall AEZ.	Mupangwa et al., 2017	Network of farm trials (3 seasons), enterprise budget analysis
Malawi	Maize mixed	Maize	CA	+		Reduced CV of yield under low (< 750 mm) rainfall.	Ngwira et al., 2013	Long-term (6-year) farm trials
S Africa (Malawi, Mozambique, Zimbabwe, Zambia)	Various	Maize	CA	+		Reduced sensitivity of yields to seasonal rainfall total. Yield advantages in 80% of cases across environments.	Thierfelder et al., 2015	Statistical analysis of multiple field trials
Mexico	Maize-beans	Maize	CA	+		Zero tillage reduced CV of maize yield, with or without residue retention. Residue and zero tillage increased average yield.	Verhulst et al., 2011	Long-term (12-year) field trial
India (Haryana)		Wheat	CA	+		No-till increased grain yield in a year with terminal heat stress, but not a normal year; net return increase in both years was greater in stress year.	Sapkota et al., 2014	Farm trials (2 years)
Various	Various	Various	CA	+		Relative yield performance of CA improves with increasing drought and temperature stress, suggesting yield stabilization under climate variability.	Steward et al., 2018	Meta-regression of 1042 yield from 85 sites in 42 publications.
Malawi	Maize mixed; cereal-root crop mixed	Maize, pulses	CA, DIV	+		Minimum tillage and crop diversification reduce downside production risk, with much greater benefit from joint adoption.	Kassie et al., 2015	Econometric, nationally-representative farm and plot survey
Zambia	Root crop; cereal-root crop mixed; maize mixed	Maize	CA, DIV, improved seed, fertilizer	+		Legume intercropping stabilizes and increases maize yield. Fertilizer and improved seed increase yield under drought stress, but ineffective under false onset (fertilizer) or heat stress (improved seed).	Arslan et al., 2015	Analysis of geo-referenced nationally representative panel data and historic climate data

Zimbabwe	Maize mixed; cereal-root crop mixed	Maize, pulses	DIV				+		Crop diversification increased mean cereal yield, income, and food security status. Stabilized yields were assumed, not demonstrated.	Makate et al., 2016	Econometric analysis of cross-sectional household data
Myanmar	Upland intensive farming	Various (pigeonpea, cotton, sesame, other pulses)	DIV	+					Local crop diversification strategy combines crops with weakly correlated yields to effectively stabilize production and income.	Matsuda, 2013	Statistical analysis of production stability, long-term (7-year) farm data; no control
Ethiopia	Pastoral		DIV				+		Herd diversification reduced months of food deficit and household food insecurity	Megersa et al., 2014	Econometric analysis of household surveys
Mexico	Irrigated	Wheat	DIV	+					Diversifying cultivars reduced yield variance up to 33% without decreasing mean yield.	Nalley and Barkley, 2010	Portfolio analysis of yield time series (1990–2002)
Mongolia	Pastoral	Livestock	IBAI		+	+	+		Improved herd recovery 2–4 years after winter weather disaster, through reduced distress selling, improved credit access to replenishing herds.	Bertram-Huemmer and Kraehnert, 2015	Econometric analysis of panel household data
Kenya	Pastoral	Livestock	IBAI		±		±	+	IBAI increases future herd size when initial size $>$ 15 TLU poverty trap threshold; either improves or impedes accumulation when initial herd size = threshold; has no effect when initial herd size $<$ threshold; Optimal scheme reduces 15-year projected poverty rate from 55% to 42%.	Chantarat et al., 2017	Ex ante, simulated herd growth with stochastic model parameterized with household panel and experimental data
Kenya	Pastoral	Livestock	IBAI		+	±	+		Increased probability of next season herd size $>$ 16 TLU, in drought and non-drought years; decreased probability of severe child malnutrition during drought years.	Cissé and Ikegami, 2016	Ex-ante, dynamic stochastic optimization model
India	Dry rainfed; rainfed mixed	Rice	IBAI			+			Increased fertilizer use, area cultivated.	Cole et al., 2017	RCT
Mexico	Various	N/A	IBAI		+	+	+		Payouts led to increased area cultivated the following year, increased per capita expenditure and income.	De Janvry et al., 2016	Regression discontinuity analysis of municipalities with and without payout.
Malawi	Maize mixed	N/A	IBAI				+		Improved perceived food security status and diversity of diet.	De Nicola, 2015	Cross-sectional household survey data analysis
Senegal, Burkina Faso	Agro-pastoral millet-sorghum (Senegal); Cereal-root crop mixed (Burkina Faso)	Groundnut (Senegal), maize (Burkina Faso)	IBAI		+	+	+		Increased area and earlier sowing of maize, fertilizer, resulting in modest crop yield increase. IBAI more effective than savings at stimulating investment in production inputs.	Delavallade et al., 2015	RCT

Cambodia	Lowland rice; tree crop mixed	N/A	IBAI		±		Increased adoption of improved technology only for relatively wealthy, when probability of a shock was known.	Falco et al., 2016	Experimental game
Mexico	Irrigated; maize-beans; dryland mixed	Maize	IBAI		+	+	8% of maize area shifted into more profitable crops. Increased maize yield average of 6%.	Fuchs and Wolff, 2016	Comparison of counties with and without IBAI
Bangladesh	Rice-wheat	Rice	IBAI		+		Increased investment in quality seed, fertilizer, irrigation, pesticides.	Hill et al., 2017	RCT
Kenya	Maize mixed	Maize	IBAI			+	Improved diet diversity and perceived food security status.	Isaboke et al., 2016	Econometric, cross-sectional survey, propensity matching
Kenya	Pastoral	Livestock	IBAI	+		+	Payouts reduced distressed livestock sales (by 64%) for better-off households; reduced food rationing by poorer households.	Janzen and Carter, 2013	Econometric, randomized annual household panel data
Ghana	Cereal root crop mixed	Maize	IBAI		+		Increased uptake of quality seed, fertilizer, irrigation, pesticides	Karlan et al., 2014	Randomized experimental study
Ethiopia	Highland temperate mixed	Various (teff, maize, sorghum, wheat and barley)	IBAI		+	+	Draught animals, credit, fertilizers, improved seeds. Insured farmers tripled savings, increased oxen ownership 25%.	Madajewicz et al., 2013	Difference-in-difference, participant vs. control villages; qualitative interviews and focus groups.
Ghana	Cereal-root crop mixed	Maize, various	IBAI		+		Meso-insurance held by lenders increases credit access by smallholder farmers.	Mishra et al., 2016	Econometric, difference-in-difference
Zambia	Maize mixed	Maize	IBAI		+		Increased area and earlier sowing of maize, fertilizer use.	Miura and Sakurai, 2015	RCT
Rwanda	Highland perennial	Maize, bean	IBAI			+	Increased average annual household income by ~US$100.	Ashimwe, 2016	Econometric, propensity matching
India (Tamil Nadu)	Rice	Rice	IBAI		+	+	IBAI prompted adoption of higher-yielding, less drought-resistant cultivar mix. IBAI improved welfare average income where basis risk was low or informal risk sharing was high.	Mobarak and Rosenzweig, 2012	Model-based analysis of RCT, panel data
Kenya	Maize mixed	Maize	IBAI		+	+	Increased use of fertilizer (50%), improved seed (65%) and maize yield (60%). Reduced manure use.	Sibiko and Qaim, 2017	Analysis of farm household survey data
Burkina Faso	Cereal root crop mixed	Cotton, sesame, livestock	IBAI		+		Cotton area-yield insurance increased investment in non-target farm enterprises (sesame, livestock)	Stoeffler et al., 2016	Randomized impact evaluation

Bangladesh	Rice-wheat	Rice	IBAI		+			IBAI availability increased demand for drought-tolerant rice seed, and bundling with this seed increased demand for insurance.	Ward et al., 2015	Choice experiments
N/A	N/A	Rice	IBAI, SAG		±			IBAI and drought-tolerant rice each stimulated demand for the other.	Carter et al., 2016	Choice experiments
India	Rice	Rice	IBAI, SAG		+			Access to insurance and access to drought-tolerant rice seed each increase demand for the other.	Ward and Makhija, 2016	Choice experiments
India (Andhra Pradesh)	Rainfed mixed or Dry Rainfed	Groundnut	SAG	+				Increased mean yield 23%, reduced variable production cost 17%. Yield variance reduction accounted for 33–46% of income benefit.	Birthal et al., 2012	Econometric
India	Rice	Rice	SAG	+				Yield advantage increases with number of days (up to 12) of flooding, with insignificant yield penalty in non-stressed conditions.	Dar et al., 2013	Large-scale (128 villages) randomized farm trial
India	Rice	Rice	SAG	+	+			43% of projected gains from SAG attributed to crowding in of labor intensive planting, fertilizer, and uptake of credit.	Emerick et al., 2016	RCT, randomly distributed stress-tolerant seed packets
Africa (13 countries)	Various	Maize	SAG	+		+	+	US$ 907–1565 million potential cumulative benefits to producers and consumers. Risk reduction projected to reduce poverty 0.01–4.29% by 2016.	Kostandini et al., 2013	Ex-ante, economic surplus model, experimental and on-farm data
Africa (13 countries)	Various	Maize	SAG			+		US$ 362–590 million potential cumulative benefits to producers and consumers.	La Rovere et al., 2014	Ex-ante estimate of impact of large-scale adoption
S Asia (5 countries)	N/A	Rice	SAG			+		Producer + consumer benefit NPV (2011–2050) from uptake of hypothetical new drought-tolerant rice in S Asia estimated at US$2.0 billion.	Mottaleb et al., 2012	Ex-ante, partial equilibrium model, crop simulation, breeder expert opinion, historic climate data
India (West Bengal)	Rice	Rice	SAG	+				Flood-tolerant rice and improved management, alone and combined, stabilized and increased yield in years with contrasting flood depth.	Sarangi et al., 2016	Farm trials (2-year)
E and S Africa (8 countries)	Various	Maize	SAG	+				Yield advantage over commercial varieties in all years, greater under stress conditions.	Setimela et al., 2017a	Farm trials
E and S Africa (6 countries)	Various	Maize	SAG	+				Yield advantage of 1.4 t ha^{-1} over commercial varieties during severe 2015/2016 El Niño event.	Setimela et al., 2017b	Farm trials

Philippines	Rice	Rice	SAG	+					Flood-tolerant rice improved yield in flood year with no yield penalty in non-flood year.	Singh et al., 2009	3-season field trials
Zambia	Root Crop; cereal-root crop mixed; maize mixed	N/A	SP	+			+		Cash transfers mitigate negative effect of weather shocks on household caloric intake and dietary diversity, with greater benefit for poorer households.	Asfaw et al., 2017	RCT, analysis of panel data and interaction with rainfall data
Ethiopia	Various	N/A	SP	−	−		±		SP participation showed modest and comparable improvement in food security and well being in drought and non-drought years, no significant influence on coping strategies, hence only marginal protection from drought.	Béné et al., 2012	Panel survey data from Productive Safety Net Program (2006, 2008)
Kenya	Pastoral	Livestock	SP, IBAI		−	+	+		IBAI and SP contribute to resilience to climate shocks, improved child health. SP increased pastoralist mobility. IBAI increased investment in production, strategic livestock sales. IBAI much more cost-effective than SP.	Jensen et al., 2014	Econometric analysis of panel data (2009–2012), randomized IBAI discounts.
Zambia	Root crop; cereal-root crop mixed	N/A	SP	+			+		Cash transfers smoothed and increased food consumption for households facing shocks. Covariate shocks, and early cash transfers before shocks, increased effectiveness.	Lawlor et al., 2017	Multi-site clustered RCT; Econometric analysis of panel data (2010, 2012)
Nicaragua	Maize - beans	N/A	SP	+			+		Cash transfer, combined with vocational training or productive investment grant, protected consumption and income from drought, and diversified livelihoods. Benefits persisted two years after intervention.	Macours et al., 2012	RCT; analysis of panel data (2005, 2006, 2008), climate data.

[a] CA = conservation agriculture; IBAI = index-based agricultural insurance; AF = agroforestry; SAG = stress-tolerant seed; DIV = diversification; SP = social protection.

[b] S = Stabilize production, livelihood; P = Protect productive assets; U = Increase uptake of capital & technology; L = Improve livelihood or welfare measures; E = Escape poverty.

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