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Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change

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Incremental adaptation may be inadequate to deal with rapid shifts and tipping points for food production under climate change. The concepts of transformative and transformational adaptation have emerged in recent years to address the need for major, non-marginal transitions in sectors, such as agriculture in response to climate change. However, there is less empirical evidence of transformation in practice. Here we use a simple semi-quantitative definition to identify recorded cases of transformational adaptation in response to climate change. A structured search of academic literature found 23 empirical case studies that meet our criteria for transformation of agriculture under climate change: a response to climate risks along with a redistribution of at least a third in the primary factors of production (land, labor, capital) or the outputs and outcomes of production over a time period of 25 years or less. The case studies offer experience-based lessons on managing transformative processes in agriculture at all four stages of the adaptation cycle: understanding goals and objectives, developing a vision and pathway, implementing adaptation actions, and monitoring, evaluating and learning. In general, the case-study processes of transformation have diverged from well-managed, inclusive approaches based on foresight and continual learning. Our review provides little early evidence that transformative adaptation processes in response to climate change have generated more resilient agricultural systems or improvements in governance. Governments and development partners could improve the effectiveness of outcomes through providing more comprehensive and long-term approaches to adaptation planning alongside financial and technical assistance, within a framework that rewards farms as multi-functional systems.

Keywords: adaptation cycle, factors of production, case studies, foresight and scenarios, governance, continual learning, empirical research

INTRODUCTION

Evidence on the impacts of climate change on natural and human systems is growing rapidly. This evidence comes from a wide variety of sources, including from farmers themselves; farmers in many places are experiencing rapid changes in phenomena, such as the traditional start of the rains, planting dates, amounts and patterns of rainfall, and frequency of extreme weather events (Postigo, 2014; Konchar et al., 2015; Abidoye et al., 2017; Kumar et al., 2018). While farmers accumulate a considerable amount of experience over their lifetimes (and the lifetimes of their forebears), in situations where the rate of change is relatively rapid, previous experience may be inadequate to adapt to novel conditions.

To date, most attention on adaptation in agriculture has gone toward incremental adjustments that may enable better management of climate risks and opportunities in the near-term (Rickards and Howden, 2012; Vermeulen et al., 2013). Given that much adaptation at the level of an individual farmer, small-scale food processor or trader involves autonomous "learning by doing," the focus on incremental approaches is understandable. Sequences of incremental adaptation actions may lead, if they are additive, to increasingly beneficial outcomes in terms of dealing with changes in climate and climate variability. On the other hand, additive incremental actions run the risk of path-dependent decisions that lock farming systems into sub-optimal trajectories. Furthermore, there is much evidence demonstrating that climate change effects on agricultural systems are neither linear nor additive (Schlenker and Roberts, 2009; Lobell et al., 2011; Vermeulen et al., 2013). Climate change impacts on poor farmers in particular may involve thresholds that are so near current conditions that incremental adaptation actions may simply be ineffective in protecting assets, livelihoods and food security (Harvey et al., 2014; Savo et al., 2016). For example, across Africa, climate projections show that critical thresholds for several crops and regions may be crossed in the next 5–20 years, pushing farmers out of their current cropping choices and farming systems (Rippke et al., 2016). Incremental adjustments in agricultural systems may not be enough to deal with the challenges that current and future generations will face: more proactive and ambitious action will be required.

A considerable literature has developed over the last few years on the concept of transformational adaptation in agriculture (Kates et al., 2012; Rickards and Howden, 2012; Mapfumo et al., 2015), perhaps emanating in response to the possibility of "major, non-marginal change" (Stern, 2006). Despite this, the term transformation in relation to adaptation remains vague and has plural definitions (O'Brien, 2012; Mustelin and Handmer, 2013; Rickards, 2013; Feola, 2014; Pretty et al., 2018). These definitions vary in vision from relatively simple changes in cropping locations through to substantial redesign of global food systems to meet societal goals for environment, livelihoods and nutrition. Not only is the term somewhat ambiguous, there is lack of clarity as to which real-world examples constitute transformation, whether it has been occurring in specific situations, and—if transformation indeed leads to desired development outcomes—how it can be facilitated.

Is the notion of transformational adaptation useful? It should be: the policy and investment implications and needs of transformational adaptation may be very different from those of more incremental adaptation (Dowd et al., 2014). If it were possible to identify those situations in which transformational adaptation were desirable or necessary, adaptation at scale would be more effective, enabling the appropriate scale of change and avoiding short-term cul-de-sacs in adaptation practice. Some incremental adaptations may inadvertently increase the vulnerability of people to climate risks. For example, promotion of single adaptation responses, such as offering small-scale farmers crop insurance or drought-resistant maize varieties, may act as a disincentive for other types of change that may lead to much more positive outcomes over the longer term, such as substituting other crops for maize, or other livelihood options for agriculture (Vermeulen et al., 2013).

In this paper we aim to assess whether transformations have occurred in agriculture in response to experienced or anticipated climate change, and to draw out the lessons on factors that have helped or hindered transformative change. We propose a simple, quantitative definition of transformational adaptation in relation to agriculture based on changes to the inputs to and outputs from agricultural systems. Using this definition, we review and characterize published case studies on transformational adaptation in agriculture. We then discuss the emergent success factors, in terms of transformative processes, that support transformational outcomes. In the conclusions we evaluate the overall findings on whether and how transformation is already happening in agriculture, and propose some actions that could be taken to promote more positive outcomes as transformational adaptation becomes a larger focus of agricultural development.

METHODS

Defining Transformational Adaptation in Agricultural Systems

The idea of transformation in agriculture is far from new. Transformation processes in agriculture have been observed, theorized about and documented since at least the eighteenth century (Timmer, 1988). These analyses generally use transformation to mean the set of structural changes in national economies by which agriculture falls in share of GDP and employment but rises in productivity. Agricultural transformation as a structural process may occur over timescales of a few decades; transformational adaptation on the other hand may occur within much shorter timescales of a few years driven in part by the rapid climate changes impacting on agricultural systems.

While the terms transformational and transformative are often used interchangeably, we find it useful to draw a distinction between them. Transformational refers to the outcome of a process, whereas transformative refers to features of the process that enable the outcome (OED, 2018[1]). For example, transformational change happens through transformative learning. A substantial portion of the literature

[1]OED is Available online at: http://www.oed.com

to date on transformational adaptation deals with identification of transformative practices and the behavior changes that drive or enable transformation. Here we aim to complement this useful body of work on transformative processes with a more empirical and outcome-oriented survey of cases where agricultural systems have undergone transformational adaptation in response to climate change. Thus, our definition for recognizing transformational adaptation places a greater emphasis on the external outcomes of transformation rather than the internal transformative features highlighted by other authors, such as Mapfumo et al. (2015).

Fazey et al. (2018) propose that transformation can be measured across three dimensions: the quality, distribution and timeframe of change. We use these dimensions to propose a simple definition of transformation in agriculture in response to climate change as a major change in inputs to and/or outputs from a system over a defined timeframe. More specifically in the agricultural system we define transformational adaptation as:

- a response to climate risks, usually in combination with other drivers (quality);
- a redistribution of at least a third in the primary factors of production (land, labor, capital) and/or the outputs and outcomes of production (the types and amounts of production and consumption of goods and services arising from multi-functional agricultural systems) (distribution);
- within a timeframe of 25 years (timeframe).

We selected the threshold of one-third change based on innovation theory, in which most common models of diffusion of innovations are asymmetric with a point of inflection below a 50% saturation level (Meade and Islam, 2006). The familiar S-shaped innovation or adoption curve arises from an assumption that income is lognormally distributed (Bain, 1963). This agrees with many observations of adoption rates of agricultural technologies: many cases of livestock-related technologies in the global tropics, for example, exhibit saturation levels of 40–50% at most (Thornton and Herrero, 2010), and the inflection points of the adoption curves will be lower than these values. Much transformational adaptation is likely to involve qualitative changes over and above quantitative changes in inputs and outputs. This would include cases where the priority outputs from multi-functional agricultural systems shift between competing goals of economic returns, food security, employment and environmental services (including greenhouse gas mitigation). We selected the timeframe of 25 years based on a human generation, which is generally understood to be 15–40 years in biological terms and 20–30 years in self-identity terms (Biggs, 2007).

Reviewing the Literature

To add to the extensive literature on theories and processes of transformation, we present a set of empirical examples where transformational agriculture, as defined above, has already happened, at least partially because of climate change. We carried out a structured search of academic literature augmented by case studies recommended by colleagues and materials from the gray literature and media to assess more recent change. To identify cases that authors described as transformative or transformational, we searched in Web of Science using the search terms "agri* transform* climate adaptation" for the years 2000–2017. After reviewing each article's abstract, we extracted those that described recent changes in an agricultural system. These 200 articles were then reviewed to identify those that report empirical information on transformation that has already happened (**Figure 1**). Other articles (not classified as relevant empirical articles for our purposes) included recommendations for adaptation planning to achieve transformational change in the future, modeling of anticipated transformations, theoretical or methodological content, and vulnerability analyses.

We reviewed all empirical articles to identify those that contained empirical data consistent with the definition of transformational adaptation as outlined in section Defining Transformational Adaptation in Agricultural Systems above. This gave a total of 15 empirical case studies of transformational adaptation in agriculture in response to a changing climate. We supplemented these cases with additional cases recommended by colleagues (cases 10–11, 14–17, 19–20), which met our criteria but were not returned by the structured search on Web of Science, giving a total of 23 case studies. In terms of selection bias in the search method, the key bias is likely to be the inconsistent use of the terms "transformation," "transformative," and "transformational" across the literature. Beyond the eight additional cases that we found via colleagues' recommendations, there may well be a much greater number of documented cases available that do not use any of these terms but nonetheless meet our criteria.

We tabulated the 23 cases, noting the type of transformation, climate risks and opportunities driving change, evidence of major (>33%) change in inputs and/or outputs, governance shift, scale (e.g., number people/territories/value chains) and timeframe (**Table 1**). We considered the dimension of governance or decision-making to be particularly important to supplement the simple "input-output" definition of transformation that we used. The "black box" of adaptation decision-making lies between inputs and outputs (Biesbroek et al., 2015) is beginning to be explored in the growing literature on transformative processes in agriculture (e.g., Park et al., 2012; Dowd et al., 2014; Mapfumo et al., 2015). We understand governance in its broad sense as the "processes of interaction and decision-making among the actors involved in a collective problem that lead to the creation, reinforcement, or reproduction of social norms and institutions" (Hufty, 2011).

To analyse the success factors and drivers of positive transformation associated with the case studies, in other words the features of the transformative change processes that lead to transformational outcomes, we used the adaptation cycle framework of Wheaton and Maciver (1999) that has been built on by Park et al. (2012), Wise et al. (2014) and Jakku et al. (2016). This framework, which has been elaborated specifically to address transformative adaptation in agriculture, conceives of adaptation as an iterative cycle of four stages:

- Problem (re)structuring, understanding the overall goals and objectives (who or what needs to adapt and why);

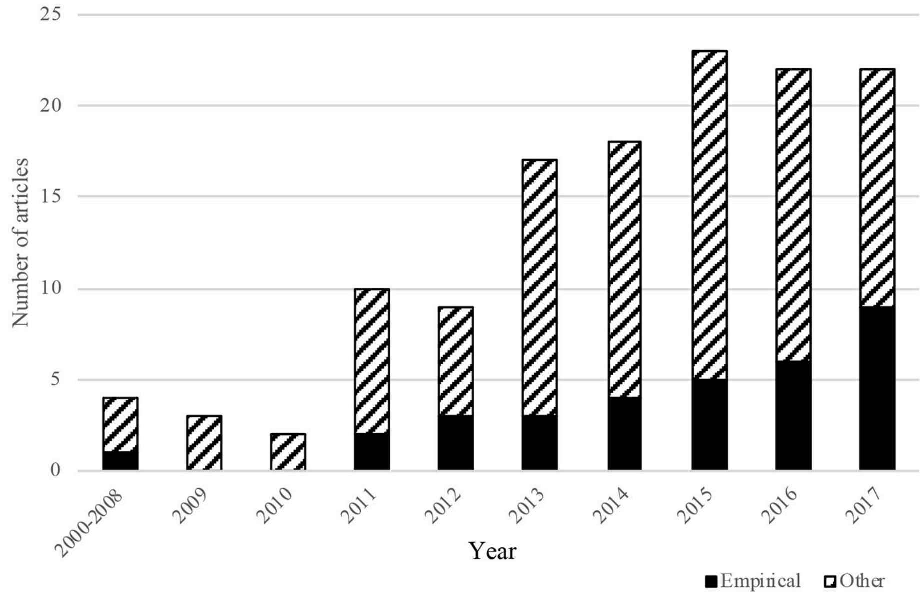

FIGURE 1 | Results of literature search for case studies of transformational adaptation in agriculture driven at least in part by a changing climate, showing number of articles by year.

- Developing the vision and identifying pathway (what are the opportunities for adaptation and what are their costs and benefits);
- Implementing adaptation actions (which methods and resources to use, understanding constraints and incentives);
- Monitoring, evaluating and learning (are changes addressing the goals and objectives).

RESULTS

A histogram of the number of articles with the search terms "agri* transform* climate adaptation" for the years 2000–2017, and describing recent changes in farming systems, is shown in **Figure 1**. The overall number of articles reached a plateau by 2015, but the number of articles giving empirical information on recent transformation has continued to increase up to 2017, the most recent search year.

The 23 case studies that meet our criteria of transformational adaptation are listed in **Table 1**, with information relating to the type of transformation in each case, the climate risks driving change, the nature of the greater-than-33% change in inputs and/or outputs, the associated governance shift, the scale of the change, and the timeframe. The spatial and jurisdictional scale of change ranged from the village level (measured in tens or hundreds of households) up to more than 10,000 km^2 in the large-scale government-driven programmes of China and Ethiopia. All timeframes fell within a single generation (25 years) as per the definition used for the literature review, but some transformations occurred very quickly, within five or fewer years, often triggered by a specific climate-driven event, such as a severe drought or pest attack. Not all transformations were associated with a clear shift in governance. In some cases, such as case 12 in India, farmers undertook major changes without accompanying shifts in decision-making. Where a governance shift did occur, it might be in response to a specific climatic change (such as new water governance in Kazakhstan in response to scarcity) or simply occur in parallel with, but unrelated to, climatic trends (changes in rice tariffs in Costa Rica and wine regulations in UK, for example).

The case studies provide considerable variety in the climate risks driving (or being perceived to drive) change: drought and water issues (reduction in availability, decreasing groundwater supplies for irrigation), land degradation through erosion and over-grazing, sea level rise, salinity problems and decreased ocean productivity, increasing frequency of extreme events, such as storms and flooding, warming and drying trends, cooler night temperatures, and increased incidence and pressure of pests and diseases. In all cases the observed transformational adaptation was only partly in response to the changing climate; multiple other drivers interact with the climatic driver (as made particularly clear in case 4 from Burkina Faso).

Several of the case studies document substantial shifts in land use and labor of croppers and livestock keepers. The most commonly observed transition was a switch in crops grown, particularly from cereal rotations to fruits or vegetables (observed in six cases, in China, India, Morocco, Mozambique and Nepal), but also from cereals to cash crops (cotton in case 5 in China and sugarcane in case 9 in Costa Rica). In a small number of cases a major new crop was introduced in a new area (peanuts in case 1 in Australia, coffee in case 19 in Nicaragua and vines in case 22 in UK). The case in Vietnam did not involve a change in crop, but rather a major shift in management strategy, from high-yielding rice to low-yielding but low-risk ratoon rice (case 23). Transitions involving animal agriculture entailed changing

TABLE 1 | Empirical case studies on transformation in agriculture under climate change.

Case	Type of transformation	Climate risks and opportunities driving change	Evidence of major (>33%) change in inputs and/ or outputs	Governance shift	Scale (e.g., number people/territories/ value chains)	Timeframe	References
1. Australia: PCA moving peanut production to Katherine, Northern Territory, Australia	Production sites moved from Queensland to Katherine region (Northern Territory).	Rainfall variability in SE Queensland region lowers productivity and profits, increases the incidence of fungus thus affecting peanut production (by 30% of value).	PCA bought 11,700 ha in Katherine region and was predicted to harvest 4,000 ha within 6–7 years. In 2008 they expected the farms in Katherine to produce a third of PCA's crop by 2012. They established new agronomic systems, new infrastructure including irrigation. However, they reversed the transformation and closed the farm.	PCA (largest peanut-growing company in Australia) translocation strategy; later a change in company governance and goals reversed the move.	A single company.	2007–2013	Marshall et al., 2013; Jakku et al., 2016
2. Bangladesh: shift to shrimp and prawn farming in Bagerhat district	Shift from rice cultivation to aquaculture of shrimp and prawn	Increased salinity due to reduced dry season flows from rivers, plus inundation from sea	Up to 70% land use change to ghers (shrimp/prawn ponds) in higher salinity areas to production of export-oriented production of black tiger shrimp and giant freshwater prawn. More recently, people have started raising mud crabs.	Development of a gher leasing market and auctions for farm products.	Three villages in Bagerhat district in South-West Bangladesh; changes typical of a much wider area	Mid 1980s to 2011	Faruque et al., 2017
3. Bangladesh: farm improvements in response to flooding	Reallocation of land from crops to aquaculture, rebuilding of homesteads to withstand floods, migration away from village.	Rising frequency and severity of floods since 2008.	Proportion of homesteads adopting the new flood adaptations has increased from 1 to 78%.	Autonomous adaptation without a governance change.	Village level (>300 households).	2008–2017.	Fenton et al., 2017
4. Burkina Faso: phased responses to environmental challenges and economic opportunities	Changes in cropping area, switches between cropping and transhumant livelihoods.	Rainfall variability drives transhumance and has some influence on cropland extent.	Extent of fields halved between 1988 and 2010 in Yomboli Village; significant reallocations of labor out of agriculture depending on opportunities (e.g., mining, development projects, urban migration)	Growing pressures on land availability and rights; development projects can create step-wise changes e.g., accessibility by road, affecting life choices and village dynamics.	Village level	1988–2010.	Reenberg et al., 2012
5. China: shifting from rice to cotton in Nanshan village	Shifting from rice production to rice/cotton mixed systems.	Frequent droughts, warming and drying trends.	Area under cotton increased to 36% in 2012, up from a very small area in 80s and 12% in the 90s.	Autonomous adaptation without a governance change.	Village level	1990–2012	Lei et al., 2016

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TABLE 1 | Continued

Case	Type of transformation	Climate risks and opportunities driving change	Evidence of major (>33%) change in inputs and/ or outputs	Governance shift	Scale (e.g., number people/territories/ value chains)	Timeframe	References
6. China: wheat-corn rotation to apple as main crop in village of Beidian, Fujian Province.	Switch from wheat–corn rotation to apple as the main crop, and corn and coarse cereals as the subsidiary crops.	Drought and dry periods causing inadequate groundwater used to irrigate crops, such as winter wheat.	Wheat-corn rotation completely phased out by 2009. Wheat-corn rotation was 100% in 1980–2000 and by 2009 it fell to 0%. From 2000 to 2012 apple trees introduced and by 2012 corn 4% of land use, coarse cereals 4%, adult apple trees 76% and young apple trees 16%.	Reforestation programme "Grain for Green" was main driving force for land use change. Shift from subsistence agriculture to market-oriented economy allowed the conversion from wheat to apple.	Village level	2000–2012	Lei et al., 2014
7. China: government grassland conservation policy in Inner Mongolia	Households shifted from grazing sheep and goats on open pasture to keeping dairy cattle in stalls. Food and fuel consumption also changed as a result.	Increasing drought, grassland degradation.	67% decreases in numbers of sheep and goats, increases in cattle, decreases in grain production, and increases in fruit and vegetable production.	Government-imposed grazing policies restricted access to grassland; city jobs offered to those in severely degraded areas who wanted to exit agriculture. Households leased pasture land to/from others. Many herders joined or created cooperative associations to support market-oriented activities.	Policies implemented in Inner Mongolia, which covers >1 million km^2 and has >25 million people. Study conducted in three regions.	Implementation piloted in Inner Mongolia in 1998 and expanded to the whole province after a few years.	Du et al., 2016
8. China: multiple land use changes in Dingcheng County, Hunan Province	1,700 ha cropland returned to lakes for fish and pearl cultivation. Introduction of new crops bamboo and camellia (for oil). Exit from farming.	Increase in area affected by drought, particularly in higher-altitude locations.	Most pronounced change in highland hilly areas, where >50% of farmers have exited farming in favor of urban employment in response to low water availability.	Land use change promoted under government's "Grain for Green" reforestation scheme.	145 km^2	1990–2010, with higher rate of change since 2000.	Zhou et al., 2016
9. Costa Rica: shift from rice to sugarcane	Abandonment of rice farming, leading to change in farming identity and social ostracization.	Reduced water availability compounded by over-allocation of scarce irrigation resources.	40% of farmers have transitioned from rice to sugarcane while others have reduced cropping area.	Removal of tariffs keeping out imported rice, coupled with rapid vertical integration of rice mills.	28,000 ha total area (under national irrigation project) with mean farm size 9 ha (1–50 ha range).	2005–2013.	Warner, 2016

(Continued)

TABLE 1 | Continued

Case	Type of transformation	Climate risks and opportunities driving change	Evidence of major (>33%) change in inputs and/ or outputs	Governance shift	Scale (e.g., number people/territories/ value chains)	Timeframe	References
10. Ethiopia: rehabilitation of degraded lands through exclosures	Rehabilitation of degraded lands through closed areas (exclosures).	Drought and desertification.	3 million ha of degraded land now under exclosure.	Progressive shift of control from NGOs to government; devolution to local communities inconsistent.	Concentrated in the Tigray region of Ethiopia (41,409 km^2).	Started in 1991; acceleration since 1996	Descheemaeker et al., 2006; Mekuria et al., 2007, 2011; Leminih and Kassa, 2014
11. Ethiopia: sedentarisation of pastoralists	Shift from pastoralism toward settled irrigated crop systems.	Recurrent droughts, decreasing rainfall, soil erosion and rangeland degradation Schmidt and Pearson, 2016.	Replacement of pasture with irrigated cotton and sugarcane. 100% of an area of over 70,000 hectares currently covered by irrigation projects, and this is to be increased. (Headey et al., 2014).	National irrigation policies and sedenterisation programs.	National/sub-national scale in the Awash valley of the Afar region of Ethiopia, which covers 72,053 km^2. Irrigation and parks projects in 1960–1970s.	Several sedenterisation programs from 1990s including 2008 Policy on Pastoral Development.	Behnke and Kerven, 2011; Headey et al., 2014; Schmidt and Pearson, 2016
12. India: changed cropping patterns in the Kashmir Valley	Switch from cereals (rice and maize) to apples, and from almonds to alternative trees (apple, pear and walnut).	Shorter winters with less snowfall (reducing irrigation supply) and warmer summers. More frequent hailstorms that damage crops.	More than 50% of farmers, at low medium and high altitudes, have reported switching crops, in response to water scarcity in the case of cereals, and high winds in the case of almonds.	Autonomous adaptation without a governance change.	Kashmir Valley is 15,948 km^2 in extent; changes recorded in villages within the valley.	Late 1990s to 2015.	Wani et al., 2015
13. Kazakhstan: reallocation of water	Formal reallocation of irrigation services, shifting to alfalfa or safflower (need less water).	Reduction in snow cover and annual water supply into irrigation infrastructure.	Decline in water supply by 40%, with this decrease distributed among farmers by water user associations.	Establishment of formal responsibilities for water supply infrastructure management, but also increasing illegality in water access.	c. 60,000 ha and 12,000 population.	Most changes 2012–2016.	Barrett et al., 2017

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TABLE 1 | Continued

Case	Type of transformation	Climate risks and opportunities driving change	Evidence of major (>33%) change in inputs and/ or outputs	Governance shift	Scale (e.g., number people/territories/ value chains)	Timeframe	References
14. Kenya: shifting from cattle to camels among pastoralists	Replacement of cattle with camel husbandry.	Reduced rainfall and drought. In 2005–06, drought led to a 70% fall in the size or pastoralists herds of cattle, goats and sheep Baird, 2008.	Between 1999 and 2009, Kenya's camel population increased by over 2 million, from 0.8 million in 1999 to 3 million in 2009.	Development of camel markets and cultural acceptance.	Pastoralist communities including the Rendille, Borana, Pokot, Maasai and Samburu are introducing camels into their cattle herds Kagunyu and Wanjohi, 2014	Trend to rear camels began after 2005–06 drought.	Baird, 2008; Kagunyu and Wanjohi, 2014
15. Kenya: adaptation and intensification in a dryland area	Shift from pastoralism to rain-fed cultivation and beekeeping.	Droughts in 1980s, and short recurrent droughts in the 1990s, as well as the severe drought in 1999–2001.	No agriculture before 1980s, only pastoralism. By 2010 almost 90% of all households in the highlands, and many in the mid-hills (ca. 60%) and lowland areas (ca. 30%) were engaged in farming. From 1986 to 2010, the area cultivated with maize increased by 72%, from 26 to 45 km^2. Beekeeping increased from 0 to >40% farmers.	Kenyan Freedom from Hunger Council encouraged pastoralists to change to rainfed cultivation in the 1980s. After 1990s drought, interventions by the government's Arid Lands Resource Management Program, including land governance.	East Pokot, part of Baringo County in Kenya's Rift Valley province. 133,189 people living in this area as per recent census figure.	1990s–2010.	Funk et al., 2005; Greiner and Mwaka, 2016
16. Morocco: wheat to tree crops	Switch from wheat to fruit trees in hillside areas.	Water availability. Vulnerability to droughts.	51 out of 111 projects for smallholders under the Plan Maroc Vert adopted climate change adaptation measures. 9,891 farmers (43%) adopted at least one adaptation measure.	Plan Maroc Vert became an overarching policy which covered all actions by the Department of Agriculture Faysse, 2015.	Provincial level.	2011–2016.	Faysse, 2015; World Bank, 2016

(Continued)

TABLE 1 | Continued

Case	Type of transformation	Climate risks and opportunities driving change	Evidence of major (>33%) change in inputs and/ or outputs	Governance shift	Scale (e.g., number people/territories/ value chains)	Timeframe	References
17. Mozambique: effective livelihood adaptation to climate change disturbance: scale dimensions of practice	Dual land use system using high elevations in the landscape to plant "insurance crops" in normal and wet years. Shifting to drought-resistant/shorter-maturing crop varieties.	Droughts, storms and flooding extremes Osbahr et al., 2008 More frequent and heavy rainfall events Usman and Reason, 2004	90% of the respondents had adopted dual land-use system, using the natural diversity of the landscape to cope with the increased frequency of droughts during the last 20 years. 45% of the respondents had shifted to drought-resistant or shorter-maturing crop types (or in some cases varieties), including rice, maize, cassava and sweet potato.	Formal farming associations initiated in 2001 and 2002 by the local community, international NGOs and the district government helped secure access to land, labor and information. Farming associations collectively develop responses to drought, heavy rains and increased variability.	Village level: population of ~600 people in 175 households.	1990s–2004.	Osbahr et al., 2008
18. Nepal: adapting in Manang in Western Nepal	Switch from buckwheat and barley to vegetables and fruit trees.	Annual and seasonal warming. Increased precipitation with changes in patterns.	72% of respondents studied reported growing a wider range of vegetable varieties, with a switch away from buckwheat and barley.	Autonomous adaptation without a governance change. Increased tourism in the region provided a market for fruits and vegetables.	Village level: population of 6,538.	No timeframe given but cites "rapid climate change"	Konchar et al., 2015
19. Nicaragua: higher altitude coffee	Diversification and improved inputs and services in response to predicted change in coffee farming locations.	Projected increase in temperatures and changes to precipitation Läderach et al., 2010 Major coffee rust outbreak in 2014 a strong driver of change.	Expected that 25,000 ha of 126,000 ha (c. 20%) will convert away from Arabica coffee IFAD, 2014. Farmers are already reallocating land areas of up to a third of farm area Cohen and Castro, 2016 plus reallocations of labor to off-farm employment (Bacon et al., 2016).	Government agencies and cooperatives work together on diversification and improved water efficiency.	National scale, in major coffee growing regions.	2014 onwards.	Läderach et al., 2010; IFAD, 2014; Bacon et al., 2016; Cohen and Castro, 2016
20. Niger: farmer-managed natural regeneration	Large-scale regeneration of native trees and shrubs in the arable landscape.	Drought, though unclear whether increasing in frequency or intensity.	In 5 million hectares (almost half of all cultivated land in Niger) a 10–20-fold increase in tree and shrub cover has been observed WRI, 2008.	Policy change to transfer tree ownership from state to farmers WRI, 2008	Primarily in the Maradi-Zinder agricultural region in Southern Niger (~6.9 million hectares); also observed in Tahoua, Dosso and Niamey regions (Reij et al., 2009).	Started in 1983 with major outcomes by 2005.	WRI, 2008; Reij et al., 2009; Haglund et al., 2011

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TABLE 1 | Continued

Case	Type of transformation	Climate risks and opportunities driving change	Evidence of major (>33%) change in inputs and/ or outputs	Governance shift	Scale (e.g., number people/territories/ value chains)	Timeframe	References
21. Peru: adaptation in the Andes	Wetland creation with modified irrigation adjustments.	Glacier shrinkage, water scarcity due to less runoff from springs and reduced river flow. Colder night-time temperatures.	Herders have switched to irrigated wetlands to water livestock; increased livestock mobility to deal with water scarcity, increased frequency of night frosts, and changing pest patterns.	Autonomous adaptation that involved a governance change. Farmers organize themselves into water boards ("juntas de usuarias") which regulate water access and maintain irrigation systems.	Departments of Puno, Arequipa, and Cusco in the Peruvian Southern Andes.	1986–2009.	Postigo, 2014
22. UK: Viticulture expansion	Large expansion in area under vines. Adoption of less robust sparkling wine varieties	Longer period during growing season above the 13°C cool climate viticultural threshold.	148% increase in grape planting area over a decade.	2006–2008 European Union reforms to wine regulations to create level playing field across Europe and with New World wines. Success of UK wine in international competitions also a factor.	Regional in the southern UK.	Rapid expansion, particularly from 2007 to 2015.	Nesbitt et al., 2016
23. Vietnam: shift away from conventional rice	Abandonment of high-productivity, high-input rice in favor of low-input, low-risk ratoon rice.	Increased frequency of early floods causes major rice crop losses.	100% shift from conventional rice to low-input ratoon rice.	Falling local government revenues has driven a shift toward farmer-led and company-led approaches to climate adaptation.	Thua Thien Hue and Quang Binh Provinces.	2002–2017	Christoplos et al., 2017

livestock kept (for example from cattle to camels in case 14 in Kenya), switching from crops to fisheries (from rice to shrimp in Bangladesh in cases 2 and 3 and from crops to fish in case 8 in China) or from pastoral livestock to sedentary cropping (cases 11 and 15 in the drylands of Ethiopia and Kenya).

Transformations that involved major changes in use of inputs included reallocation of water resources (by croppers in case 13 in Kazakhstan and by livestock keepers in case 21 in Peru) and reallocation of labor, including dropping farming in favor of off-farm labor or migration to urban areas (in three cases, in Bangladesh, Burkina Faso and China). Two cases entailed transformation of land use to sustainable land management on a large scale: livestock exclosures over three million hectares in Ethiopia (case 10) and farmer-managed regeneration of on-farm trees over five million hectares in Niger (case 20). Notably these two cases were not labeled as transformative or transformational in the literature.

In the case studies, transformations most often occurred because livelihoods that used to be viable became increasingly untenable or stressed. Adaptation is not necessarily about trying to maintain the status quo in production while the context changes; several of the case studies demonstrate a complete inability to carry on doing the same things as previously (e.g., case 17 from Mozambique, case 9 from Costa Rica and case 15 from Peru) while others were in response to opening up of options that were previously closed, such as the adoption of cash crops, fruit trees and vegetables with the potential to generate higher earnings (e.g., case 22 on cool climate vineyards in the UK or case 16 on fruit trees in Morocco).

DISCUSSION: SUCCESS FACTORS AND DRIVERS OF POSITIVE TRANSFORMATION

Understanding Goals and Objectives

Problem-restructuring and assessment of goals and objectives can take place at farm level by individual farmers or can happen at larger village, district or provincial scales. In the cases of shifting from rice to shrimp and prawn farming in Bangladesh (case 2), the increased water salinity over time forced farmers to change the species reared. Salinity rates varied from pond to pond, so the transition was not made by all farmers at the same time. They individually assessed their problem (increasing salinity) and adjusted their practices as necessary. Case 14 on the shift from cattle to camels in Kenya is a similar change in which pastoralists made individual decisions to alter the balance of species in their herds so as to better respond to drought. In other cases, such as case 10 in Ethiopia and case 20 in Niger, the problem of land degradation within the ecosystem was recognized on a large scale and the overall goal was to rehabilitate the landscapes to improve conditions for all inhabitants.

There are concerns around spatial heterogeneity, including differing personal goals and objectives of farmers. There can be big differences in change strategies even if resources are similar, and furthermore, the goals, objectives and trade-offs for individual farmers may change through time. For example, in case 9 in Costa Rica, farmers prioritized two goals in their adaptation decisions: security of well-being (maintenance of productive assets, education and healthcare for the whole family) and personal identity as self-reliant rice farmers. Taking the decision to switch to sugarcane in response to the combined pressures of climate change and restructured rice markets involved a difficult trade-off between security and identity. Despite differences among individuals, some transformational adaptation options necessarily need to be implemented on scales larger than a single farm, such as the grassland conservation policy implemented by the government in the Chinese region of Inner Mongolia (case 7) or the large-scale regeneration in Niger (case 20). These types of initiatives often need support and a certain amount of coordination from a central authority. In the Inner Mongolia case, farmers were given options by the government to leave agriculture and to relocate to cities for work, depending on their own personal goals.

Temporal differences associated with transformational adaptation also exist. Some options may be clearly aimed at the short term, such as weather-index-based insurance for crops or livestock, while other adaptation options may operate over longer time spans, such as changes in crop type owing to gradual increases in temperature, for example. Many changes in farming practice may have temporal issues associated with them, and these may involve trade-offs between the benefits accruing to famers in the long term and the short term along with changes in relative costs. For example, a farmer may lose access to a piece of land while waiting for certain cash crops to produce harvestable yield (e.g., case 6 in China of switching from wheat-maize rotation to apples; case 10 of land exclosures for rehabilitation in Ethiopia; and case 16 of wheat to tree crops in Morocco), or they may be waiting to harvest additional firewood from regenerated tree cover. Poorer farmers may not be able to wait for these longer-term benefits to materialize at the expense of short-term profit foregone.

These temporal trade-offs may not just be economic. For some adaptation interventions, there may be significant trade-offs between meeting (shorter-term) food production or income objectives and longer-term, strategic objectives relating to sustainable development. Farmers' decisions on crop residue management and altering the integration of crops and livestock within a mixed farming system reflect these trade-offs (Thornton and Herrero, 2015). While a focus on incremental adaptations in response to short-term variability is often seen as a logical and viable entry point into adaptation to climate change over the longer term, successful short-term risk management does not necessarily imply successful longer-term adaptation (Juhola et al., 2016). Past government policies can also alter the vulnerability of agricultural systems to climate change. For example, the goal of economic transformation of agriculture in Ethiopia has involved widespread promotion of large-scale irrigated monocultures, which may have inadvertently increased the climate risks to agricultural livelihoods (case 11).

Developing the Vision

Decisions about adaptation to (and mitigation of) climate change impacts can be characterized by considerable uncertainty.

Such uncertainty may add considerable complexity to decisions involving many different sectors of society and/or considerable up-front or recurrent investment costs particularly when dealing with more transformational adaptation. Nevertheless, relevant, reliable and timely knowledge is essential to inform the design of appropriate adaptation actions and to both inform and support and the critical foresight and visioning aspects. Important sources of uncertainty include the future trajectory of greenhouse gas emissions during the remainder of the current century, and uncertainty associated with different climate models that can be used to project impacts into the future (IPCC, 2014).

As with the problem structuring and goal setting, the development of a vision and pathway can take place at several different scales. In case 1 of the Peanut Company of Australia, the corporation adjusted its strategy to include relocation of its operations to a place with an expectation of a more favorable climate. It encouraged farmers to translocate in anticipation of future climate change. In this case the vision and pathway were determined by a private sector entity in consultation with landholders and governments, in both the new and old locations (Jakku et al., 2016). In other cases the pathway is set by the government, as in the case of grassland conservation in China (case 7) and the encouragement of sedentarisation of pastoralists in Ethiopia (case 11). In some cases, the pathway is defined more by outside forces, such as market opportunities. For example, in Nepal (case 18), farmers switched from buckwheat and barley to vegetables and fruit trees partially because of warming temperatures and changes in precipitation patterns, but also because increased tourism in the region provided an expanding market for fruits and vegetables. The pathway may have looked different if such a market had not developed.

In the Nicaragua example (case 19, **Table 1**), foresight was used to identify future risks to coffee production ahead of farmers' experience, through the use of downscaled climate change models to identify likely future climate risks (Baca et al., 2014). The Nicaraguan Government's National Adaptation Plan for agriculture places priority on the adaptation of smallholder coffee farmers' livelihoods, and international investment is being used to support climate change adaptation actions within the coffee supply chain (Vermeulen et al., 2013). In these systems, tradeoffs do exist between diversification and intensification adaptation alternatives that may require sophisticated policy formulation and implementation, but the inherent uncertainty around the future climate is not a major concern in defining appropriate policy in this situation, given the consensus between climate models as to temperature increases in the coming four decades.

Research and institutional capacity to project climate impacts, together with awareness-raising efforts, can enable the first steps of adaptation to "leapfrog" ahead of local experience. In the Australian case (case 1), while economic analysis of shifting production regions was undertaken, much of the vision for transformational change appears to have been due to awareness of climate change and the resultant increase in risk for the industry in its earlier location, spurring action to adapt by partial relocation. This was embedded in the mental models of how people think the world operates, and what it could look like from their (peanut production) perspective in several years' time (Marshall et al., 2013; Jakku et al., 2016) notwithstanding significant uncertainty in projected rainfall changes. This kind of visioning is probably very common.

Complex problems do not always need complex solutions; low-cost, high-impact measures can cut through complexity and accelerate adoption. For example, case 2 on the shift from rice to shrimp and the subsequent management of increasing salinity, there was a fairly straightforward solution to a problem that had multiple causes.

The case studies illustrated a wide range of visioning and foresight tools. These include scenario and sensitivity analysis to assess thresholds in systems, projecting the need for a different type of adaptation: transformation may be needed in some situations, while in others, incremental change may be adequate to address farmers' objectives. In other cases, long-horizon whole-farm economic analyses can help determine whether interventions are likely to be sustainable or self-sustaining, or whether they will require some kind of subsidy. Similar types of analysis can help to evaluate the local effectiveness of portfolios of different interventions at the level of the farming household (e.g., case 1 in Australian peanut production systems and case 16 in Morocco with the shift to tree crops under the Plan Maroc Vert) or to understand the pathways of change (e.g., case 4 in Burkina Faso, in which four different tools are applied).

Implementing Adaptation Actions

In some cases, the implementation of adaptation actions is more proactive to anticipated future changes, while in other cases the actions are reactive to the changing climate. In the case of higher altitude coffee in Nicaragua, for example (case 19), the projected increases in temperature and changes in precipitation prompted a government-led program (NICADAPTA) co-financed by multilateral development banks to help coffee farmers proactively adapt to the predicted changes. The program involves a package of interventions that promote crop diversification, increase water use efficiency, strengthen markets and institutions, and provide weather information services to farmers. Farmers' autonomous adaptations (see cases 3, 5, 12, 18, 21, 23), which are often reactive, contrast with adaptation programmes driven externally by government or development agencies. Indeed, the capacity of governments to drive implementation of adaptation programmes may be over-estimated. In Vietnam, for example (case 23), low financial capacity in government at district level has led district officials to defy national and provincial directives to raise rice productivity, and instead give tacit support to local farmers' strategies for climate adaptation, such as low-yielding ratoon rice that is less prone to losses from flooding and salinity.

Many of the case studies demonstrate clearly the benefits of collective action: on-ground action in existing multi-stakeholder platforms to address context specificity and facilitate engagement, involving interactions with many different types of partner, contributing to increased social capital and strengthened local enabling environments. Collective action can be beneficial for several reasons. In Niger (case 20), it increased social capital, decreased costs and helped share knowledge in farmer-managed natural regeneration. In China (case 8), it empowered a newly formed vegetable-growing cooperative to meet common economic and environmental challenges. Ultimately, collective action helped farmers overcome economic, social, technical and capacity barriers. It can also help achieve thresholds of scale and equitable outcomes for producers (Bouamra-Mechemache and Zago, 2015). Thus, adaptation programmes should strengthen local organizations rather than focus purely on technological innovation.

In Bangladesh, farmers whose way of life had become untenable due to severe floods were completely dependent on social networks to learn about adaptation solutions, such as new house-building methods, in the absence of formal assistance (case 3). Of course, defaulting and free-riding on collective agreements and trust-based networks can also be an advantageous adaptation strategy for the individual farmer, as evidenced by the increase in illegal water abstraction in Kazakhstan as water has become more scarce (case 13). Farmers can also take advantage of differential access to climate adaptation solutions and technologies to improve their own market position. For example in Jamaica only wealthier farmers have been able to access the 150 greenhouses built nationally, partly in response to rising rainfall variability; they have subsequently driven down vegetable prices and excluded poorer farmers from key markets (Popke et al., 2016).

Significant changes in farming practices and institutions will require clear rights and incentives, and in cases where economic benefits may arise only in the longer term or where adaptation objectives may have to be de-emphasized in the short term, strategies will be needed to bridge the gap between initial investments and these longer-term benefits. Different case studies have addressed the temporal trade-offs in different ways. In Niger, for example, food-for-work programmes initially supported natural regeneration (case 20). In Kenya, rapidly developing markets for camel hides enhanced the transition from cattle to camels (case 14). Such "early wins" may reinforce local support in helping to make a vision of transformation a reality (Jakku et al., 2016).

Monitoring, Evaluation and Learning

Appropriate monitoring systems allow adaptation outcomes to be tracked through time, to pick up as early as possible indications of how adaptation (transformative or otherwise) is working or not. In case 6, documenting a shift from wheat-maize rotation to apples in China, Lei et al. (2014) conducted an in-depth study to learn how land use changes related to alleviating the impacts of drought on agriculture. Quantitative analyses, such as this can help other organizations and governments assist farmers and communities in making informed decisions on the possible pathways available to adapt and transform their own agricultural practices. In case 19, a "results framework" enables appropriate monitoring of progress toward planned outcomes including improved land and water management, enhanced capacity, resilience of infrastructure and knowledge management (IFAD, 2012). In addition to monitoring progress, generating and sharing lessons from adaptation efforts on a systematic basis can help them be scaled out, including internationally. Case 20 is an example of farmer managed natural regeneration in Niger, and the experience has proved useful to other countries in the region (Nyasimi et al., 2014).

For several of the case studies, as yet there is little information on the household-level impacts of the changes described. Where transformations are not permanent or not entirely positive (e.g., case 11 on sedenterisation in Ethiopia and case 9 on sugarcane farming in Costa Rica), monitoring and evaluation could provide a timely and critical corrective. Follow-on responses, such as policy and market support may be critical for sustaining change, at least in the near term as trade-offs with longer-term goals are most prominent. In case 14, the shift from cattle to camels has contributed substantially to income generation within the Borana community, although the full benefits are hampered by the prevalence of camel diseases, the use of less productive breeds and limited markets for camel meat (Kagunyu and Wanjohi, 2014)—all of which could be solved more effectively through responsive government policy based on regular assessment of challenges and implementation of solutions.

Monitoring, evaluation and learning is not necessarily easy, especially in cases where transformation is driven by autonomous efforts of farmers or community groups, such as in case 21 from Peru. The most effective use of external investments into monitoring, evaluation and learning may be to support approaches developed by communities themselves. For example, among flood-prone coastal Bangladeshi farmers, social learning networks have been the key to survival, through rapid sharing of technologies and strategies (case 3) and could be supported to enable continuing adaptation to future system changes (as recommended in case 2). In Ethiopia (case 10), communities have successfully self-organized to conduct labor-intensive monitoring. Ultimately, however, sound monitoring, evaluation and learning by themselves cannot assure achievement of desired outcomes. Case 1 provides an example: while PCA, the largest peanut growing company in Australia, has relocated some of its production, over 95% of peanuts are still grown in Queensland, despite many producers' awareness of the likely challenges of climate change in the future (Marshall et al., 2013). In studies of Australian adaptation, Dowd et al. (2014) found that those engaged had far-reaching information and knowledge network connections coupled with relatively weak social links to family, friends and colleagues—weak ties in this case empowering transformative change.

CONCLUSIONS AND WAYS FORWARD

Conclusions: Is Transformation Happening?

Is transformational adaptation already happening in agricultural systems in response to climate change? In the simple input-output definition of transformation established in this article, the answer is yes: the 23 empirical case studies reviewed provide multiple examples of non-marginal change (more than a third change in inputs or outputs) within the last generation (25 years) in a wide range of agro-ecological and socio-economic contexts, and from village to national level (**Table 1**). Outcomes from transformational adaptation to climate change are likely to become better understood over time, with increasing numbers of empirical studies (**Figure 1**). It is not yet clear that the transformative adaptation processes observed in these case studies have generated more sustainable agricultural systems. In cases where transformation drives toward a single option, such as a switch to a different crop type, there is a danger that the new system is as maladaptive as that which it replaces. For many farmers, transformative pathways that open out a wider set of options may be more useful than specific switches in inputs or outputs.

Our simple working definition of transformation may not capture the full nature of "major, non-marginal change" intended by proponents of transformative responses to climate change. Prevailing adaptation theory and practice have been criticized for an emphasis on technological diagnoses and solutions that deny the more fundamental drivers of vulnerability to climate change: weak and inequitable access to resources, services, decision-making and justice (Chandra et al., 2017). The capacity to adapt to climate change is enhanced by basic human development, such as education and healthcare, as well as by climate-specific actions, such as early warning systems (Lemos et al., 2007). Some authors argue that successful adaptation depends on investments both in generic capacities and in climate-specific, sector-specific capacities (Eakin et al., 2014). A more overtly political position posits that transformational adaptation requires a redistribution of power within society (Blythe et al., 2018). In this light, positive transformational adaptation in agriculture would involve a transition of, or disruption in, food system governance toward more equitable participation and outcomes for marginalized producers, workers and consumers (Feola, 2014).

Our empirical research has uncovered very few examples that deliver meaningful rebalancing of participation and outcomes within food system governance. Nonetheless, the case studies do reveal how shifts in governance, particularly those in favor of disadvantaged groups, may be pivotal to transformational outcomes in adaptation. Most strikingly in Niger, the transfer of tenure over trees from the state to farmers—addressing basic control over assets rather than a technical climate change issue—was a critical success factor. The capacity of producers, processors and consumers to adapt depends strongly on public policy, market forces and cultural norms that shape access to resources and economic opportunities, as shown in Bangladesh, China, Costa Rica, Ethiopia, Kenya, Morocco, Nepal and Vietnam. Shaping the conditions for governance and learning across public policy, markets and local institutions is a key way in which governments and development partners can help provide the right enabling conditions for future adaptation, whether incremental or transformative.

Ways Forward: Supporting Positive Transformational Adaptation

The adaptation cycle framework proposes a purposive, pro-active, systematic and sequential process by which agricultural systems might adapt incrementally, or transform. While all the case studies show some of the four elements of development of goals and objectives, visioning, implementation and monitoring, none of them conform fully to the managerial logic of the adaptation cycle framework. Rather, transformative adaptation processes more usually happen through a somewhat disorganized combination of proactive and reactive responses to external drivers by individual farmers, companies or public agencies. Climate change may be a direct or indirect driver.

Where the adaptation cycle works well, it creates a strong basis for effective action, meaningful learning, and beneficial outcomes for farmers and food supply (Park et al., 2012). Therefore, investments to get this cycle working effectively for both incremental and transformative adaptation are likely to be valuable. What could governments and development partners do to improve the effectiveness of transformative adaptation leading to transformational outcomes? First, more comprehensive and long-term approaches to adaptation planning could be undertaken. Actions could include the following:

- Expand the remit of adaptation planning to consider the multi-functionality of agriculture and a system-wide view of food production and consumption. In practical terms, this would entail visioning, planning, implementation and evaluation of, desired agricultural futures in terms of ability to supply benefits to nutrition, livelihoods and environment, over and above benefits to national-level food security, monetary returns and balance of trade. It could also include outlook for technological breakthroughs, policy reframing, or disruptors on the demand-side.
- Apply the "stranded assets" thinking that has become well-established in the energy sector as a frame to encourage consideration of more transformative options for adaptation (for example, the re-siting or re-scaling of processing facilities, transport links and other infrastructure in major agricultural sub-sectors).
- Include arrangements for transformative adaptation in processes, such as the Global Stocktake of the UNFCCC, and institutions, such as the Green Climate Fund, and development bank loan and grant frameworks.

Second, a range of technical and financial assistance could be offered, in ways that promote more equitable governance and outcomes. Actions here could include:

- Support more systematic multi-stakeholder approaches in key agricultural sub-sectors to shared visioning and identification of adaptation options that are robust across a wide set of possible climate and market futures, and that include an explicit appraisal of the winners and losers from alternative options.
- Provide financial compensation for transformative changes that are deemed necessary for long-term viability of an agricultural sub-sector but incur near-term losses to the agriculture and food industries, particularly for small-scale farmers and businesses with comparatively low access to technologies and services.
- Provide support for appropriate monitoring systems so that adaptation outcomes can be tracked through time by farmers and food system participants themselves, to give early warning

of possible detrimental changes and to build the evidence base as to what is working, where and why.

- Appraise implementation of adaptation-oriented policies that entrench incremental or *status quo* behaviors among farmers—such as insurance schemes and production subsidies—in light of potential need for more transformational change.
- Invest in information and knowledge systems that provide farmers and other food system participants with the tools to forecast and envisage possible futures and to monitor and evaluate progress toward those, to support the ongoing generation of transformative options.

An important shift at the global level will be a move toward understanding—and economically rewarding—farms as multi-functional systems that deliver not only calories and profits but also good jobs, health and nutrition, environmental benefits (importantly greenhouse gas mitigation and biodiversity conservation) and cultural value. As discussed here, such a shift will entail governance that is more equitable in terms of inclusive decision-making and distribution of outcomes.

AUTHOR CONTRIBUTIONS

All authors wrote text, in addition SV conceived and edited paper, DD compiled and analyzed cases. SH and LC applied adaptation cycle framework. PT framed transformation analysis and edited paper.

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