



REVIEW

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Climate-smart agriculture global research agenda: scientific basis for action

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Abstract

Background: Climate-smart agriculture (CSA) addresses the challenge of meeting the growing demand for food, fibre and fuel, despite the changing climate and fewer opportunities for agricultural expansion on additional lands. CSA focuses on contributing to economic development, poverty reduction and food security; maintaining and enhancing the productivity and resilience of natural and agricultural ecosystem functions, thus building natural capital; and reducing trade-offs involved in meeting these goals. Current gaps in knowledge, work within CSA, and agendas for interdisciplinary research and science-based actions identified at the 2013 Global Science Conference on Climate-Smart Agriculture (Davis, CA, USA) are described here within three themes: (1) farm and food systems, (2) landscape and regional issues and (3) institutional and policy aspects. The first two themes comprise crop physiology and genetics, mitigation and adaptation for livestock and agriculture, barriers to adoption of CSA practices, climate risk management and energy and biofuels (theme 1); and modelling adaptation and uncertainty, achieving multifunctionality, food and fishery systems, forest biodiversity and ecosystem services, rural migration from climate change and metrics (theme 2). Theme 3 comprises designing research that bridges disciplines, integrating stakeholder input to directly link science, action and governance.

Outcomes: In addition to interdisciplinary research among these themes, imperatives include developing (1) models that include adaptation and transformation at either the farm or landscape level; (2) capacity approaches to examine multifunctional solutions for agronomic, ecological and socioeconomic challenges; (3) scenarios that are validated by direct evidence and metrics to support behaviours that foster resilience and natural capital; (4) reductions in the risk that can present formidable barriers for farmers during adoption of new technology and practices; and (5) an understanding of how climate affects the rural labour force, land tenure and cultural integrity, and thus the stability of food production. Effective work in CSA will involve stakeholders, address governance issues, examine uncertainties, incorporate social benefits with technological change, and establish climate finance within a green development framework. Here, the socioecological approach is intended to reduce development controversies associated with CSA and to identify technologies, policies and approaches leading to sustainable food production and consumption patterns in a changing climate.

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Introduction

Globally, agricultural and forestry systems are expected to change significantly in response to future climate change, manifesting as major transitions in livelihoods and landscapes [1-4]. During the few past decades, crop yields have been reduced because of warming [5], and the results of modelling studies suggest that climate change will reduce food crop yield potential, particularly in many tropical and midlatitude countries [6-9]. Rising atmospheric CO₂ concentrations will decrease food and forage quality [10]. Price and yield volatility likely will continue to rise as extreme weather continues, further harming livelihoods and putting food security at risk [11]. Global demand for agricultural products, be they food, fibre or fuel, continues to increase because of population growth, changes in diet related to increases in per capita income and the need for alternative energy sources while there is less and less additional land available for agricultural expansion. Agriculture thus needs to produce more on the same amount of land while adapting to a changing climate and must become more resilient to risk derived from extreme weather events such as droughts and floods.

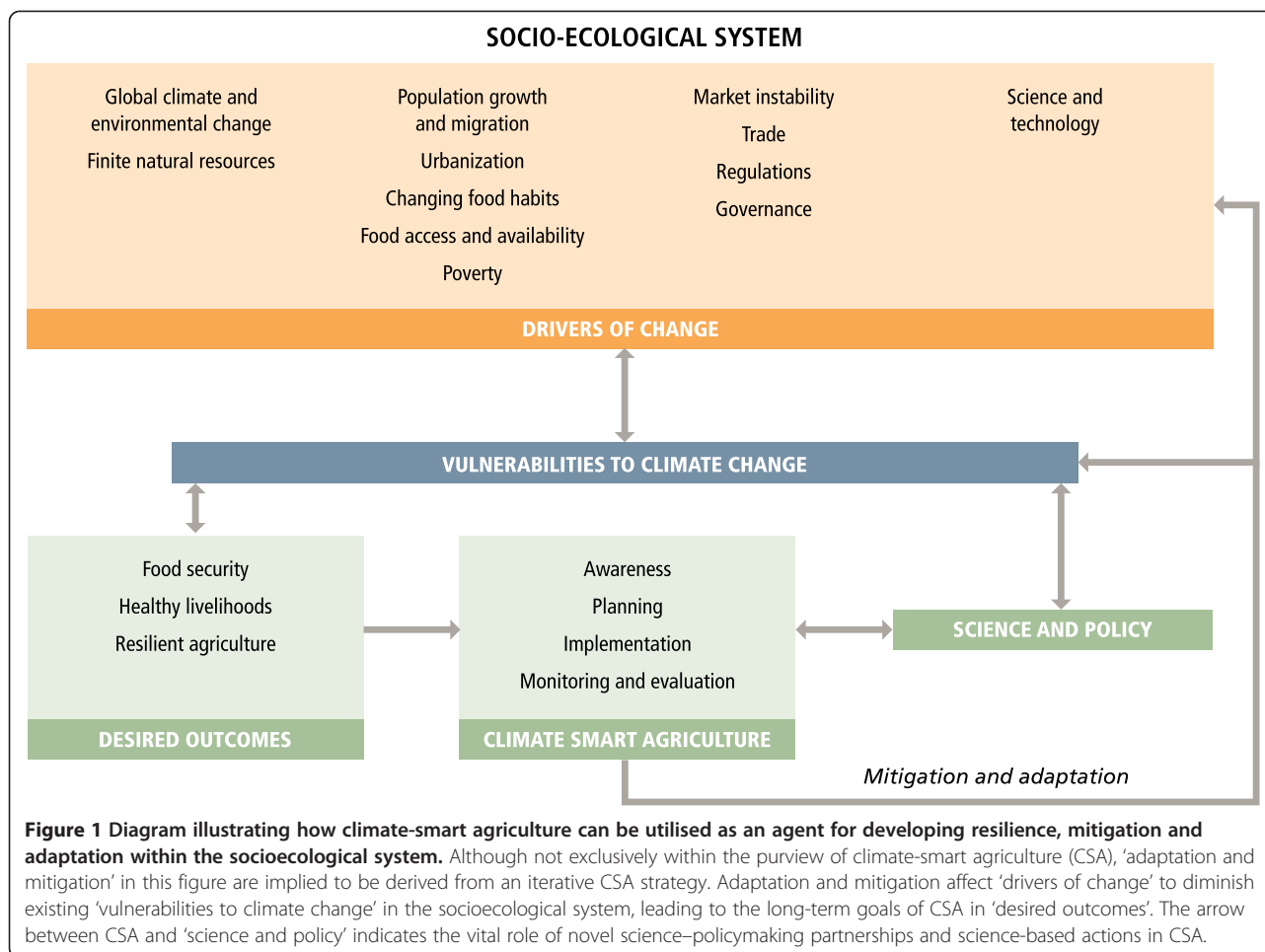
The term *climate-smart agriculture* (CSA) has developed to represent a set of strategies that can help to meet these challenges by increasing resilience to weather extremes, adapting to climate change and decreasing agriculture's greenhouse gas (GHG) emissions that contribute to global warming (Figures 1 and 2). CSA also aims to support sustainable and equitable transitions for agricultural systems and livelihoods across scales, ranging from smallholders to transnational coalitions. Forming a core part of the broader green development agenda for agriculture [12-14], CSA focuses on meeting the needs of people for food, fuel, timber and fibre through science-based actions; contributing to economic development, poverty reduction and food security; maintaining and enhancing the productivity and resilience of both natural and agricultural ecosystem functions, thus building natural capital; and reducing the trade-offs involved in meeting these goals. It invokes a continuous, iterative process for stakeholders, researchers and policymakers to meet the challenges presented by climate change and collectively transform agricultural and food systems towards sustainability goals [15]. Increased awareness and adaptive management are essential components of the CSA strategy. Yet, CSA is controversial. Such a broad agenda can be appropriated to support conflicting agendas or promote specific ecosystem services [16]. GHG emission mitigation by resource-poor farmers raises equity as an issue in developing countries because it may bring farmers little benefit unless it directly provides them with adaptive capacity. Setting CSA in the context of a safe operating space for humanity with socioecological systems

that support adaptive management and governance will require scientific metrics and science-policy dialogues [16] that depend on strong engagement of the scientific community.

At the 2013 Global Science Conference on Climate-Smart Agriculture (Davis, CA, USA), participants examined the state of global science and best practices concerning climate and agriculture worldwide. Participants built on the consensus achieved at the 2011 Global Science Conference on Climate-Smart Agriculture conference (Wageningen, the Netherlands), agreeing on a broad strategy for science and policymaking to strengthen food security, mitigation and adaptation [17]. Participants further examined current gaps in knowledge, identified existing and promising work within CSA and formulated agendas for interdisciplinary research and science-based actions to support CSA.

The relationship between vulnerability, resilience and adaptation was an overarching theme echoed across the conference and is crucial to CSA. *Vulnerability* describes exposure, sensitivity and capacity to respond to negative impacts of climate change, and *adaptation* is the means by which to reduce the vulnerability. Here *resilience* is regarded as the capacity to tolerate disturbance, undergo change and retain the same essential functions, structure, identity and feedback and is not indicative solely of returning to the same state that existed prior to a perturbation or disturbance [18-20]. Resilience focuses on factors that enable functioning despite adverse conditions [21,22], provides a means of framing the dynamic relationships between humans and the environment (socioecological systems) and considers society's capacity to manage change [23]. Thus, the principle of resilience can guide transformative change needed to meet the demands of food security, natural resource protection, and development, as well as to diminish vulnerability and promote adaptation (or adaptive capacity).

The recent increase in extreme weather events (climate shocks) threatens disruptive impacts on agriculture [24,25]. Projected adaptive actions include improving plant performance (for example, nutrition, yields, food quality) in response to elevated CO₂ and rising temperatures [26-28]; avoiding pest damage and food waste [28,29]; developing forecasting, management and insurance options to decrease the risk due to unexpected rainfall patterns, higher temperatures and shifting length in growth seasons [14,28,30]; and managing natural resources at the landscape and regional levels to assure the environmental quality and ecosystem services upon which agriculture depends [31-33]. Solutions involve trade-offs. For instance, planning now for higher temperatures and declining precipitation in arid zones may reduce water deficits for agriculture, but it will require institutional investment to support both the intensified demand for ground and



surface waters [34,35] and the necessary improvements in irrigation efficiencies [36]. Along with these adaptive actions, CSA seeks to contribute to the mitigation and reduction of GHG, mainly nitrous oxide (N₂O) and methane (CH₄) emissions, and to balance trade-offs with food security and livelihoods [7,37,38]. For example, combining agroforestry, afforestation and conservation efforts with agriculture to meet global food demand will help to mitigate GHG emissions, support biodiversity and concomitantly preserve ecosystem services [39,40]. Other trade-offs that occur when abrupt environmental changes stress agricultural systems include changes in rural and urban human migration patterns, as well as loss of cultural resources, which reduces the ability to manage land use effectively [41-43].

Without doubt, the development status of a country or region will influence the approach to mitigating and adapting to climate uncertainty and will affect the implementation and focus of the CSA strategy. For example, industrialized nations focus more strongly on mitigation of climate change through reduction of agriculture’s environmental impacts, whereas developing countries’

approaches to climate uncertainty emphasize stabilizing and boosting food production, improving incomes and building adaptive capacity [7,15,44]. Gender can also influence decisions and capacity for mitigation and adaptation. Women in some regions in Africa have experienced greater exposure and vulnerability, especially to extreme events, than men, but they also have demonstrated greater collective action in farming decisions linked to social networking [45,46].

Crucial science questions and challenges for food systems in the face of climate change and uncertainty require comprehensive, collaborative investments and science-based actions. In the past few years, policies and programmes have included landscape-scale research on food security and natural resources, policy and governance to achieve agricultural resilience to climate change and capacity building [47]. Under CSA, transformative changes to achieve food security, poverty relief, mitigation and adaptation target novel types of science–policymaking partnerships and involve stakeholders and decision-makers in the public and private sectors to gain long-term commitment and investment to carry the new actions

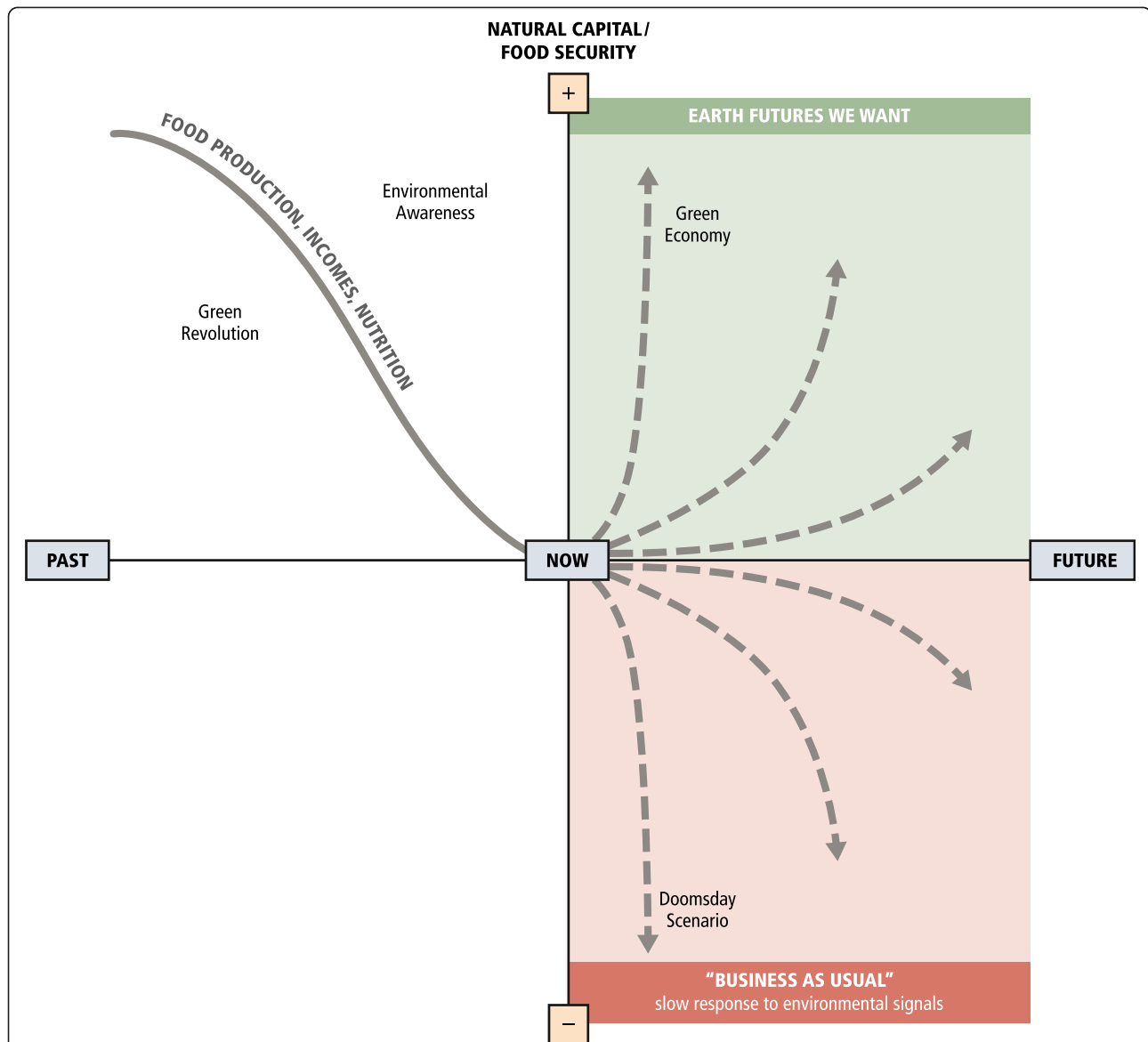


Figure 2 Schematic of the historical trajectory of food production, incomes and nutrition within the socioecological system with respect to food security and natural capital over time juxtaposed with potential future outcomes. Placement of ‘environmental awareness’ indicates that this factor gained prominence in the socioecological system as food security and natural capital diminished with respect to the trajectory of food production, income and nutrition. Positive outcomes are shaded in green, and the ‘business as usual’ and ‘doomsday’ outcomes are shaded in orange. Climate-smart agriculture plays a role in building positive outcomes such as the ‘green economy’. Adapted with permission from M van Noordwijk (personal communication, 2014).

to fruition. CSA emphasizes the involvement of scientists with farmers, land managers, agroforesters, livestock keepers, fishers, resource managers and policymakers (stakeholders) to empower them in the formation of palatable choices to enact adaptive capacity and resilience ‘on the ground’ and within broader policies [14,15]. Farmer-led innovative approaches and social learning are crucial parts of this process, where social learning represents a ‘change in understanding that goes beyond the individual to become situated within wide social units or communities of

practice through social interactions between actors within social networks’ [48,49].

In this article, we summarize and synthesize the discussions and ideas presented at the 2013 CSA conference by an international community of scientists, growers, policymakers, research scientists, government officials, nonprofit entities and students who are working to achieve food security, poverty reduction, mitigation and adaptation within the CSA context. The three sections of this article reflect the scientific themes presented at the conference: (1) farm

and food systems, (2) landscape and regional issues and (3) institutional and policy-related aspects. Within the first and second themes, parallel sessions at the conference charged participants to identify knowledge gaps, research initiatives and transformative actions required to address these specific issues. We provide a summary of the 12 sessions and highlights of the oral presentations by subject experts, and we conclude with recommendations offered during discussions as well as a consensus agenda for future actions [50]. Finally, broad outcomes and messages are presented, largely adhering to the actual proceedings to reflect the spirit and outcomes of this conference. Thus, the emphasis is on structuring disciplinary and interdisciplinary science in a CSA context rather than mechanisms for implementing science in action. This article is intended to serve as a benchmark and guide for future CSA research activities.

Theme 1

Farm and food system issues: sustainable intensification, agroecosystem management and food systems

Considerable research on climate change and agriculture exists at the farm and food system levels, including topics such as farming practices for mitigation of agricultural GHG emissions, choice and adaptation of crops and livestock to new climate regimes, decision-making by farmers and life-cycle assessments [51-55]. The tendency has been to apply disciplinary science that informs particular problems and solutions for agriculture, as demonstrated by the topics of the six sessions in theme 1. Sustainable intensification, focused initially on increased agricultural production and food security, has now moved to a broader set of goals with multiple social, ethical and environmental dimensions [56,57]. The integrative challenge for CSA is to better understand the trade-offs and choices farmers must make for greater multifunctionality and resilience to climate change. Because planning for climate change can be highly farm-, commodity- and context-specific, especially in response to extreme events, CSA is committed to new ways of engaging in participatory research and partnerships with producers [14].

Crop physiology and genetics under climate change

Responding to effects of climate change (for example, changes in nutrient availability and plant nutrient acquisition, higher CO₂ concentrations and temperatures, water deficits and flooding) that influence the closure of the yield gap between potential and actual production will require continuation of existing 'best management practices' coupled with improvements in agronomic management practices and crop-breeding [58,59]. Uncertain is the degree to which advances in crop physiology and genetics will continue to support higher agricultural production in response to more frequent

climate shocks. Whereas successful crop adaptation to new production locations may be a good predictor of future outcomes, much higher CO₂ concentrations and temperatures are conditions beyond our current set of experiences [21,60]. Molecular approaches and genetic engineering will foster better understanding and manipulation of physiological mechanisms responsible for crop growth and development, as well as the breeding of stress-adapted genotypes [61-63], but there are social controversies surrounding the use of some of these technologies. High-throughput phenotyping platforms and comprehensive crop models will lead to more rapid exploration of genetic resources, enabling both gene discovery and better physiological understanding of how crop improvement can increase tolerance to environmental stress [64-68]. Development of new crop genotypes to meet the need to thrive under future management and climate conditions, the expected increases in the frequency of climate shocks and the uncertainty of rates of climate change presents a challenge. The specific examples set forth in the following paragraphs demonstrate how greater understanding of biochemical pathways, plant traits and phenotypes and germplasm evaluation could help overcome bottlenecks in both yield and development of physiological resilience to environmental stresses.

Molecular approaches provide opportunities to establish linkages between biochemical pathways and physiological responses. In cereals such as rice, grain yield is highly dependent on the carbohydrate source (top leaves) and sink (florets) relationship, which is strongly influenced by the plant hormone cytokinin [69]. Cytokinin production also affects drought tolerance and senescence, and isopentenyl transferase (IPT) expression controls upregulation of pathways for cytokinin degradation. Therefore, it follows that tolerance of abiotic stress by delaying stress-induced senescence through manipulation of IPT expression in transgenic lines could maintain optimal levels of cytokinin, resulting in greater fitness and more seed and grain production [62]. When exposed to varying drought intensities pre- and post-flowering, transgenic rice with higher IPT expression maintained consistently higher grain yields and concentrations of sucrose and starch compared to the wild-type genotype. The delayed onset of drought-related symptoms in the transgenic lines caused positive source-sink relationships for a relatively longer period with higher photosynthetic rates than the wild type.

Combinations of multiple plant traits to survive stress, however, may produce more resilient crop production in the face of climate change [64]. Survival strategies employed by plants include early flowering to escape drought periods, stomatal control to prevent water loss, enhanced root growth in deeper soil layers to access water [70] and reduced leaf growth to minimize the transpiring

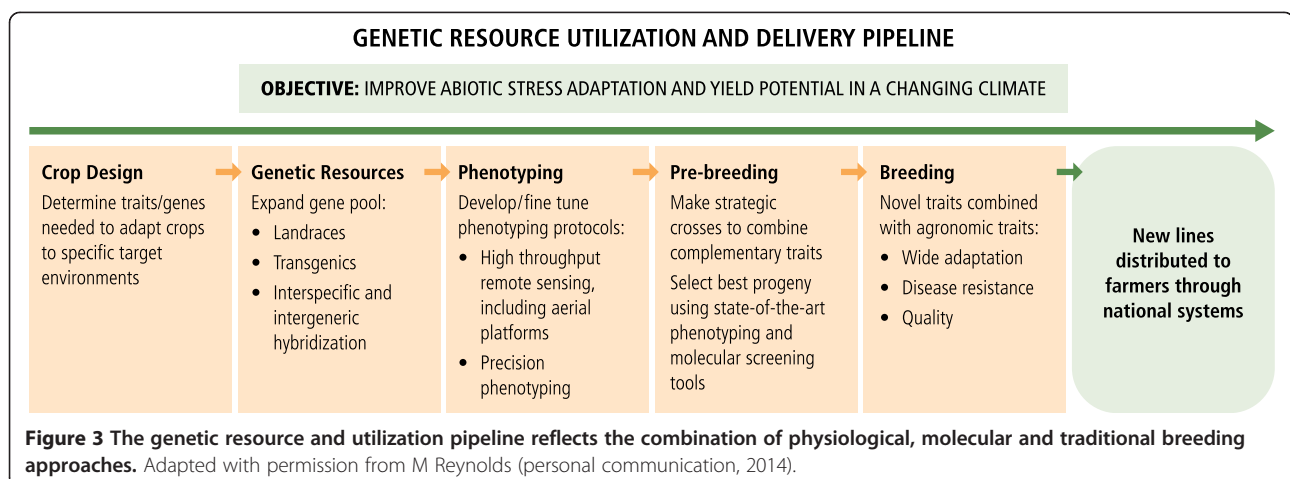
surface [71]. These adaptations come at a cost, where reductions in the growth cycle, light interception and carbon (C) assimilation by photosynthesis are often accompanied by a higher C requirement to build additional plant roots, especially under nutrient stress [72]. Thus, the trade-offs of introducing new plant traits must be considered for specific types of environmental stress [65].

By examining the genetic basis of physiological mechanisms and environmentally induced stress responses, crops such as maize, wheat and other cereals can be bred to produce better yields and tolerances through targeted accumulation of alleles that confer robust responses to environmental stressors such as drought [73] (Figure 3). This approach is used by the International Maize and Wheat Improvement Center for the discovery and accumulation of drought-adaptive traits in wheat and maize germplasm from wild-type crop relatives and cultivars from a wide range of climates and growing conditions [65,67,74]. Screening for physiological traits can be highly effective in selecting such lines for a breeding programme. Canopy temperature (CT) is an example of a widely used, high-throughput germplasm screening tool. CT is linked to stomatal conductance, an indirect indicator of water uptake by roots, especially under drought and heat stress [75,76]. In one study, researchers found that 60% of variation in yield from recombinant inbred lines grown under drought conditions was explained by CT [77]. Screening for physiological traits in candidate genotypes as an initial step may thus accelerate the search for novel genes [75] and genotypes that will be needed to deal with rapid changes in climate, such as the greater intensity and frequency of drought. Trait-based breeding programmes will be most effective when approaches are developed to simultaneously screen a broad array of genotypes for phenotypic responses to environmental stresses quickly (for example see, [78]).

Complementary approaches are necessary for solving complex physiological plant responses to climate and management. Changes in temperature, precipitation, water delivery, salinity and CO₂ concentrations will occur simultaneously. Direct experimentation, high-throughput screening platforms using molecular-based techniques and predictive modelling are a set of tools for achieving multiple goals [79-81], which include exploration of genetic resources for broader use and dissemination, gene pool expansion and yield stability in the face of interannual weather variation. In addition, these tools can help with other crop selection criteria, including quality of food and feed, source-sink relationships, pest and disease resistance, plant-microbe interactions that reduce CH₄ and N₂O emissions, and postharvest storage [60,81]. Regional networks that examine environmental and physiological tolerances and yield potentials, as well as their coalescence into global crop improvement networks [82], will provide large-scale screening approaches to assessing both germplasm and phenotypic responses of crop plants. These networks already exist in representative target environments, such as the Network for the Genetic Improvement of Cowpea for Africa, Sorghum and Millet Networks, International Wheat Improvement Network, International Maize Improvement Network; and other regional networks linked to CGIAR that focus on grains and legumes in Africa, Latin America, the Caribbean and Asia. They also include networks for research and extension supported by Association for Strengthening Agricultural Research in Eastern and Central Africa. Participatory breeding by farmers and other stakeholders will eventually be an essential way to advance this agenda [83,84].

Livestock management and animal health

Livestock production not only contributes to climate change via GHG emissions (see [85]) but also suffers due to extreme weather events and disease related to



climate change. Direct and indirect challenges in both mitigation and adaptation include fluctuating feed prices, habitat changes, expansion of vector-borne diseases in warm climates, impaired reproduction, pasture quality and availability and physiological heat stress [86,87]. Opportunities for mitigating emissions include dietary manipulation, genetic improvement and mortality reduction to enhance overall production potential; manure management; and reduction of deforestation and pasture burning through payments for ecosystem services [88,89]. Adaptation strategies include income and livelihood diversification by mixing crop and livestock production; sustainable intensification through pasture regeneration or destocking; diversifying livestock feeds; manipulation of rumen microbial composition; matching animal breeds to local environments and moving animals to other sites; and better risk management and transformative change (for example, exit from or entry into animal agriculture) [88,90-92]. These strategies rely heavily on sustainable intensification, as in the improvement of productivity and efficiency that exists in conjunction with incentives and investments that allow systems to intensify and in the development of regulations and limits on intensifying systems, among other aspects [93]. Access to credit or savings, land and resource inputs, and livelihood diversification are other potential pathways towards adaptation and food security [94,95]. Technology, supporting policies and investments will require varied mixtures of strategies, as shown by the examples described in the following paragraphs.

Flexibility in livelihood options for pastoralist, agropastoralist and ranching communities can increase a household's capacity to manage risk and adapt in the face of burgeoning external stress [96]. Adaptation options depend on household objectives and attitudes; local access to natural resources, inputs and output markets; and sustainable intensification. Nutrient management is fundamental to maintaining a livelihood in livestock production. In Madagascar, external nitrogen (N) inputs are not commonly used to replenish the N losses that occur through erosion, leaching, GHG emissions and harvest. Hence, Alvarez *et al.* [97] examined N flows through crop-livestock systems to determine management scenarios leading to improvement in their N use efficiency, productivity and economic viability. They evaluated four intensification scenarios for system productivity, food self-sufficiency and gross margins: (1) using supplementary feed (N inputs) to increase dairy production; (2) applying mineral N fertilizer to increase crop production; (3) improving conservation of manure N during storage and soil application; and (4) combining scenarios 1 and 3. They found that gross margin increased in response to improved retention of manure N and that increased N supply through supplementary feeding (scenario 4) across farm types led to increases in whole-farm N use efficiencies

from 2% to 50%, in N cycling from 9% to 68% and in food self-sufficiency from 12% to 37%. An example of adaptation to manage risk in East Africa is pastoralists who have shifted from cows to camels, which are better-adapted to survive periods of water scarcity and able to consistently provide more milk [98]. Risk adaptation by farmers may also involve changing from cultivated crops to livestock, as crops may be more environmentally and spatially constrained in the pastoralists' home regions [99].

Mitigation options at farm to regional scales form a large part of Brazil's multifaceted approach to managing direct and indirect GHG emissions from livestock. Brazil's commercial cattle industry is the largest in the world (more than 170 million head in 2006), and emissions from raising cattle are responsible for about half of the country's total emissions [100]. The principal targets for mitigating GHG emissions associated with cattle production in Brazil are reduction in deforestation and enteric fermentation, regeneration of secondary forest, recuperation of degraded pasture and soils and elimination of fire in pasture management. Maintenance of grazing productivity and high stocking rates through pasture reclamation and adoption of integrated crop-livestock systems, such as rotational grazing and introduction of legumes in pastures, buffers pressure on deforestation. Such pasture regeneration creates a potential for increasing soil C storage, with increases of up to 0.72 Mg of C-ha⁻¹.yr⁻¹ reported under improved management [101]. However, other pasture maintenance practices increase emissions. For example, burning accounted for 1.69 CO₂eq (Mt from total biome) in the Cerrado ecosystem from 2003 to 2008. Key mitigation efforts include reduction in enteric CH₄ emissions by genetic stock improvement and dietary manipulation [91]. This dietary manipulation through grain supplementation increases forage digestibility and reduces enteric fermentation, but it leads to greater emissions of N₂O through the use of fertilizers to grow the grain [100]. Several other promising technologies include grass and legume species with lower GHG emission potential, additives (for example, ionophores and secondary plant compounds such as tannins) and use of propionate precursors in feed to reduce methanogenesis [102]. To complement farm-based efforts, uniform and fair economic procurement and incentivized policies must be in place and enforced across the supply chain in order to establish supply and trade chains with low C footprints. Regional and national policies must contain mechanisms that balance market pressure to convert from low-impact land uses (for example, forests) to relatively more intensive uses (for example, ranching). The Norwegian Agency for Development Cooperation (NORAD) and the Brazilian organization Aliança da Terra, which includes farmers, researchers and agribusiness entrepreneurs, are partnering to increase contributions by

private landowners throughout the Brazilian Amazon and Cerrado to the goals of the Reducing Emissions from Deforestation and Forest Degradation (REDD+) programme by combining sustainable rangeland economic development with forest and water protection [103].

Effectively managing emerging zoonotic diseases and outbreaks due to climate change is a strong component of maintaining agropastoralist livelihoods. Increased temperatures due to climate change will affect the survival of pests in the winter and thus distribution of pests and diseases (for example, zoonotic, endemic, emerging, foodborne and noninfectious diseases), though some regions may find relief from these existing pressures in a changing climate. The Emerging Pandemic Threats Program (PREDICT) addresses the broad geographic issues in disease emergence from farm to national to global scales related to a shifting climate [104,105]. The programme, which is run within the US Agency for International Development, leverages existing networks within national and local governments as well as networks of scientists and specialists involved in outbreak reporting, microbial characterization and pathogen discovery [104]. The programme includes 20 developing countries where hotspots of emerging infectious diseases exist and is focused on surveillance of human–animal interfaces where transmission is more likely. PREDICT is focused on the prevention of pandemics by addressing underlying ecological, economic and social drivers of change, such as shifts in land use from forested systems to livestock. It is used to develop and deliver new technologies (such as information management and communication tools) to improve control efforts close to the pathogen's source. This type of interdisciplinary effort that moves from farm-level to broad spatial scales is considered necessary for creating comprehensive strategies for the control and prevention of emerging zoonotic diseases in a changing climate [104].

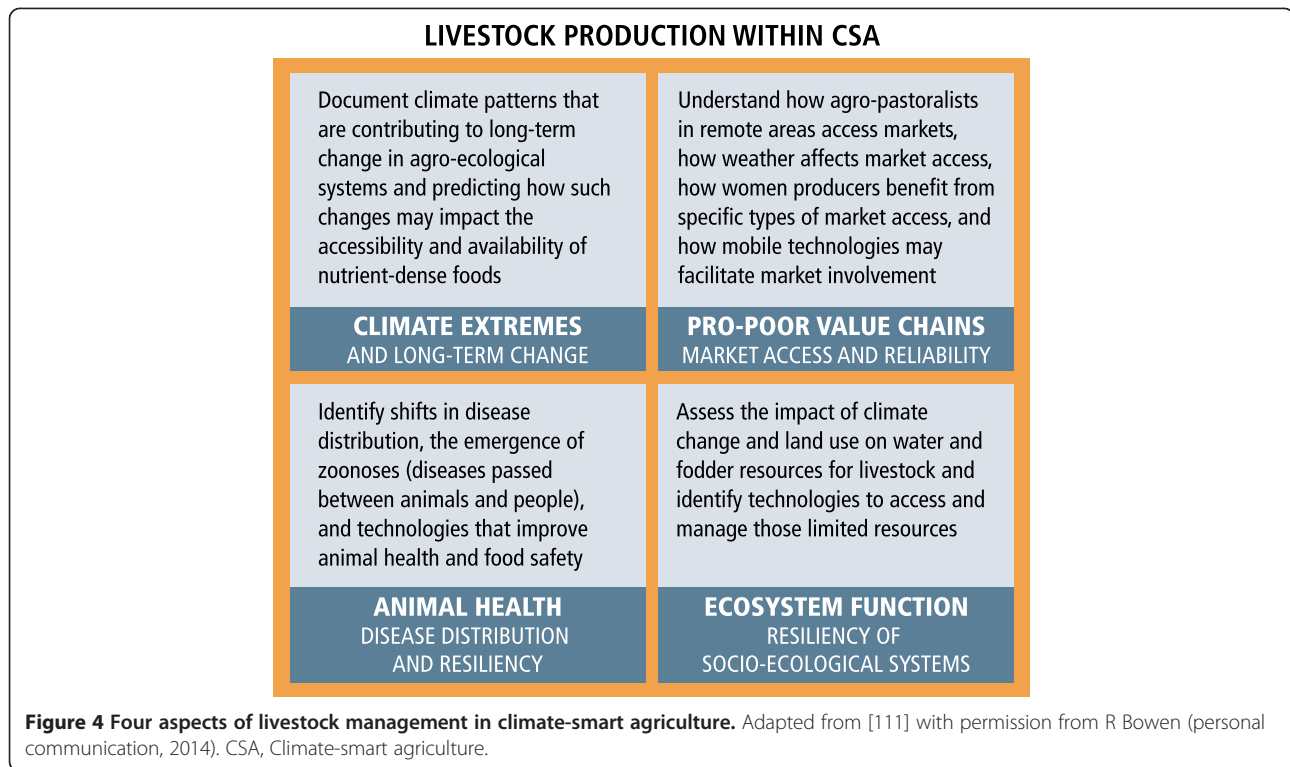
In support of agropastoral farming systems, models must integrate mitigation options, alternative intensification pathways, zoonotic disease and vector ecology (for example, genetic shifts, patterns of emergence); mechanisms of effecting behavioural change; and adaptation to future climate change scenarios. Some existing models for predicting regional GHG emissions from livestock production include BEEFGEM (Ireland; [106]), IFSM (USA; [107]) and SIMS_{DAIRY} (UK; [108]). Reisinger *et al.* [109] recently evaluated different metrics on the integrated assessment model, MESSAGE, and the land-use model, the Global Biosphere Management Model (GLOBIOM), to examine the global costs of abatement strategies used to reduce the magnitude of climate change and subsequent effects on regional food production and supply prices for livestock products and other agricultural commodities. Other transformative approaches to livestock

production include identifying the value of a blend of market-orientated smallholders vs. large-scale farms, evaluating ecosystem services payments as a means of income diversification, forming institutional and market mechanisms for reaching smallholders to foster technological change, finding the best locations for both livestock production and marginal land rehabilitation, and creating new capacity of the livestock sector for mitigation and adaptation in the face of climate change [90,110] (Figure 4). The social and economic impacts (for example, income stability, human nutrition, product value chains, transaction and opportunity costs of other alternatives) of land-sparing and reducing livestock consumption, two recently suggested mitigation options, merit further investigation, especially with respect to gender, region and income differentiation [92].

Nitrogen management: agricultural production, greenhouse gas mitigation, and adaptation

Future food security will continue to rely on N fertilizer inputs, but cropping systems must achieve yield potential (that is, close the yield gap) while minimizing trade-offs in air, water and soil quality [58,59]. The long-term ramifications of N-related GHG emissions; off-site movement of N on eutrophication, acidification and pollution of aquatic and terrestrial ecosystems; and human health problems have led to a recommendation that anthropogenic inputs of reactive N to terrestrial ecosystems be reduced by up to one-fourth of present quantities, or about 35 million tonnes of N per year [112]. Even if this reactive, anthropogenic N entering agroecosystems is emitted as N₂ rather than N₂O, the energy associated with the Haber-Bosch process and transport of fertilizers will still contribute to GHG emissions [113]. Cropping system diversification, careful selection of crop rotations to reduce nutrient loss, and improved soil organic matter content are means by which to promote sustainable intensification. Yet, this often involves a set of complex trade-offs for producers and their livelihoods [114], emphasizing the need for a CSA strategy that involves stakeholders from the beginning to develop viable scenarios that include both mitigation and adaptation to climate change. The examples presented here demonstrate how strategies for N fertilization practices provide both mitigation and adaptation benefits by decreasing GHG emissions, reducing reliance on synthetic mineral fertilizer and enhancing food security.

Enhanced-efficiency fertilizers (EEFs), such as slow-release fertilizers or those containing nitrification inhibitors and urease inhibitors, hold potential to mitigate GHG emissions. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report [114], the mean mitigation potential of N₂O by nutrient management using nitrification inhibitors and slow-release fertilizers has been estimated to be 0.07 t



CO₂-eq-ha⁻¹.yr⁻¹ (as a reference, agriculture accounted for an estimated 5.1 to 6.1 GtCO₂eq.yr⁻¹ in 2005, which amounts to 10% to 12% of total global anthropogenic emissions of GHGs). In practice, N₂O emissions decreased by 54% from a no-till corn–dry bean rotation receiving urea, urease and nitrification inhibitors in comparison to a urea-only application in Colorado (USA) [115]. According to a recent global meta-analysis of enhanced-efficiency fertilizers, nitrification inhibitors can reduce N₂O emissions by 38% and polymer-coated fertilizers by 35%, on average, compared to conventional fertilizer, but urease inhibitors alone are not as effective in reducing N₂O emissions [116]. Nitrification inhibitors are compatible with both chemical and organic fertilizers, making them a seemingly attractive mitigation option, but their efficacy varies with edaphic factors. For example, EEF materials were applied to rainfed corn in the central Corn Belt (Midwest region, USA), a more humid region than Colorado [117]. Although all EEF treatments had lower cumulative emissions than the treatment that did not include EEFs, episodic N₂O emissions from EEF treatments corresponded to rainfall patterns, and the relative effectiveness among EEF materials was similar. Together, these findings suggest that the impact of EEF materials may be diminished in rainfed agriculture systems compared to irrigated systems with regulated water availability. Although yield responses to EEF materials may also vary with respect to crops and location, consistent yield increases in corn (central

Corn Belt) grown with EEF materials were reported to occur as a result of the increased duration of photosynthetic leaf area during grain-filling [118]. In microirrigation systems, the results are less impressive, likely due to the increased efficiency of EEF where fertilization by fertigation matches crop needs more precisely, leaves less residual fertilizer and avoids its loss [119]. With this emerging evidence that use of EEF materials could have a positive impact on crop production and limit N₂O emissions, the results of research on understanding the conditions for which these materials are useful could underpin both the development of risk assessment tools and the feasibility of grower adoption of these technologies.

Mitigating GHG emissions through C sequestration depends on the stability of soil C pools. Declining productivity in the rice–wheat cropping systems of India’s Indo-Gangetic plains has been attributed to reductions in soil C [120]. Mandal *et al.* [121] found that, to combat this, addition of NPK fertilizer during double-rotations of rice led to increases in soil organic C stocks compared to adding just N or NP alone [121]. When compost was applied during rice production, as much as 29% of compost-derived C was stabilized [121]. This was attributed to high lignin and polyphenol content in crop residue and compost and also to the diminished soil C decomposition stemming from anaerobic conditions due to soil submergence under rice cultivation. Crop residue management improves poor soil fertility through soil

organic matter accumulation, leading to reductions in soil N loss by leaching and gaseous emissions; in many situations in developing countries, however, crop residues are used to feed animals, to provide fuel for cooking or are turned into biochar [122,123]. Developers of mitigation strategies for increasing soil C and decreasing N₂O emissions have to take into account the dynamics of crop residue, tillage and nutrient management, along with climate, in order to evaluate the efficacy of different practices across locations [124].

Legumes, a form of ecological intensification, offer both mitigation and adaptation options, especially to smallholder farms susceptible to deficits in soil fertility, climatic uncertainty and reduced economic access to agricultural inputs such as mineral fertilizer. The biologically fixed N from legumes is often tightly synchronized with plant N demand and has a much lower C footprint than industrially produced synthetic N fertilizers [125]. For instance, intercropping with N-fixing trees in Sub-Saharan Africa were found not only to reduce reliance on fertilizers but also to enhance soil C sequestration and reduced N₂O emissions [126]. In this intercropping system, 10.9 Mg C·ha⁻¹·yr⁻¹ were sequestered in the soil. The potential for N₂O mitigation was only 0.12 to 1.97 kg N₂O·ha⁻¹·yr⁻¹ [126]. However, the authors of a review of 71 site-years of pasture, cropping and agroforestry systems indicated that providing N additions via legumes can increase accumulation of soil C at rates greater than can be achieved with other crops, such as cereals or grasses, even when they are supplied with N fertilizer [125]. Furthermore, intercropped mixtures of peas and barley (*Hordeum vulgare* L.), compared to the respective sole crops, were found to lead to effective weed suppression in weed communities across sites in Western Europe [127]. Adaptation options that include legumes to reduce dependence on fossil-fuel derived fertilizers include integration of intercropped or rotational legumes into management regimes, development and facilitation of access to new legume cultivars with broader stress tolerance and removal of barriers to legume use and consumption in the food system (for example, competing uses, seed availability, labour).

The design of more efficient N management strategies will only be conducive to climate change solutions if based on knowledge systems and participatory research with stakeholders to ensure viable action and adaptive management. Although decision-making support tools and metrics are being developed to aid producers in tempering N inputs for the desired outcomes of higher crop production (for example, quantity and nutritional quality) and lower environmental impacts [128], adoption is a major obstacle. When extension agents are involved in troubleshooting with and training of participants, the new knowledge systems that are created begin to

delineate clear pathways that benefit farmers' livelihoods. In regions dominated by smallholder farmers who are already experiencing climate impacts such as increased drought, flooding or heat waves, the priority is on adaptive measures for reliable N availability to support food security and minimize vulnerability. Combining low inputs of synthetic N fertilizers with practices that increase soil quality through organic matter management and acquisition of N from biological N fixation allows adaptation measures to contribute to GHG mitigation. However, synthetic N sources are fraught with constraints such as high cost, price fluctuations and availability, whereas biological N sources are affected by constraints of labour, time and physiological tolerance. Future food security also will depend on a substantial rate of yield gains for major cereal crops. Maintaining these yield increases above a 1% annual growth rate will require constant improvement in crop yields, stress avoidance and agronomic management to achieve physiological yield potential [129]. However, maintaining a compounding rate of yield increases is not consistent with historical trends and likely is not achievable without great effort [130]. Therefore, the limits of current crop productivity need to be estimated using potential yield and water-limited yield levels as benchmarks. Determining and closing the yield gap, especially in developing countries, is fundamental to achieving food security because variety improvement through breeding and genetic modification might be insufficient [129,131,132].

Farmer decision-making and barriers to the adoption of climate-smart agriculture practices

Climate change challenges farmers' decisions by altering risks and uncertainty and incorporating new information into their traditional knowledge-processing systems. The unfolding of the decision-making process and its translation into action depends on the socioecological context in which farmers are embedded. How well innovation models apply to all climate-related behaviours is a major question, especially given that governance regimes at the national and international levels strongly influence farmers' actions [133]. The massive literature on innovation systems has established the basic hypothesis that farmers evaluate the costs and benefits of different practices in light of information accessed through social networks and other communication channels. The diffusion of innovation model can provide critical insights into adoption decisions. In this model, adoption of innovations follows a sequence of stages: knowledge, persuasion, decision, implementation and confirmation [134]. Innovations generated by agricultural research are communicated by extension agents to farmers. This approach may place too much emphasis on traditional socioeconomic variables and ignore how other social factors (for example, networks, gender, social norms, values, climate-change attitudes), and uncertainty may be

implicated by practices that are ostensibly consistent with CSA priorities (for example, adoption of new crops and cultivars or changes in N fertilization) [135-137].

Effective outreach strategies will manifest with greater understanding of farmers' beliefs about climate change and their readiness to respond to climate change through mitigation and adaptation. Little is known about farmers' and their advisors' willingness to use outreach tools, their information needs with respect to climate change or their ability to incorporate this knowledge into existing decision-making processes. A survey of almost 5,000 farmers in 22 top corn-producing watersheds across the United States showed that farmers' climate change beliefs correlated with both their perceptions of climate risk and their willingness to respond and adapt to changing conditions [138]. Farmers who believed that climate change is occurring, and is due in large part to human activity, were significantly more likely to support both mitigation and adaptation actions and also more likely to support government- and farm-level GHG reduction efforts. Most farmers supported adaptive strategies, with two-thirds agreeing that they should take efforts to protect land from increased weather variability. Many (59%) expressed lower levels of support, however, for mitigation through GHG reduction. These farmers obtained much of their information through social networks that included professional advisors. A survey of corn grower advisors, including government, nonprofit, for-profit and agricultural extension personnel, found that advisors are more influenced by current weather conditions and 1- to 7-day forecasts than by longer-term climate outlooks [139]. The advice given to farmers has been based predominately on historical weather trends and focused on short-term operational decisions rather than on long-term strategies. For climatic data to be useful to such populations, designing outreach strategies that target extension agents and other professional advisors will increase the potential to influence beliefs and practices of farmers. Furthermore, though mitigation policies alone might not resonate with farmers, those that combine mitigation with adaptation could be effective. In general, adoption of best management practices can be promoted by focusing on implementation among farmers most likely to adopt them, followed by leveraging social networks to inform other farmers about the benefits of adoption [140].

The constraints that farmers face when making decisions, such as whether to use conservation agricultural techniques, may create barriers to practices that could improve resilience to climate change. Conservation agriculture includes practices such as minimum mechanical soil disturbance, permanent organic soil cover and crop rotation, all of which typically increase soil C storage, especially when applied in concert [141,142]. Cited benefits of conservation agriculture in Sub-Saharan Africa

include increased yields, reduced labour, improved soil fertility, reduced erosion and land-saving [141-143]. Reports of conservation agriculture's widespread adoption may be overrated, though, because many farmers seem to adopt technologies only while incentives are offered and the project is actively supported, and then they quickly return to their former crop management practices once project support ceases [144]. Constraints to adoption include strong competition for mulched crop residues for livestock feeding, increased labour demand for weeding (which often changes cultural gender divisions of agricultural work) and lack of access to and/or use of herbicides and other inputs [143,144]. Although there are some recognized factors that influence adoption (for example, larger farm size and more education), no universal variables seem to explain adoption [145], leading some to suggest that conservation farming may be successful only under certain agroecological conditions [144,146].

Recent work in Zambia may help to explain regional variation in farmer adoption and rejection of conservation agriculture practices. Analysis of surveys of rural incomes and livelihoods revealed that rates of rejection in Zambia were high (approximately 95%), and practice dropped from 13% to 5% of farmers between 2004 and 2008 [145]. Rainfall data reveal that, during the past 10 years, the onset of the first rains needed for planting have been progressively delayed. Although adoption decisions are not strongly or explicitly based on labour constraints, farmer age or education level, farmers in districts that experience more rainfall variability are more likely to adopt conservation agriculture practices and to implement those practices with greater intensity [147]. Because conservation agriculture allows planting to occur as soon as the rains begin, it offers an adaptive response to changing rainfall regimes [148].

Fundamentally, an existing lack of food security and farmers' concerns about poor health will counteract incentives to their adoption of new farming technology [149,150]. Although many farmers believe climate risk is real, they are less likely to believe it is caused by human behaviour. They have paid the most attention to climate variables that have traditionally constrained their operations and have relied on an existing suite of adaptive behaviours [53]. Thus, knowledge networks are especially critical to their understanding of trade-offs between the short-term costs and longer-term benefits of adopting new farming technology and practices that will help them mitigate and adapt to the effects of climate change as well as to increases in climate variability. Adaptation to climate change and the idea of climate change itself define and change human cultures. Indeed, cultural factors (for example, place attachment, value systems, individual and collective identities) shape how people support and respond to adaptation interventions and must be

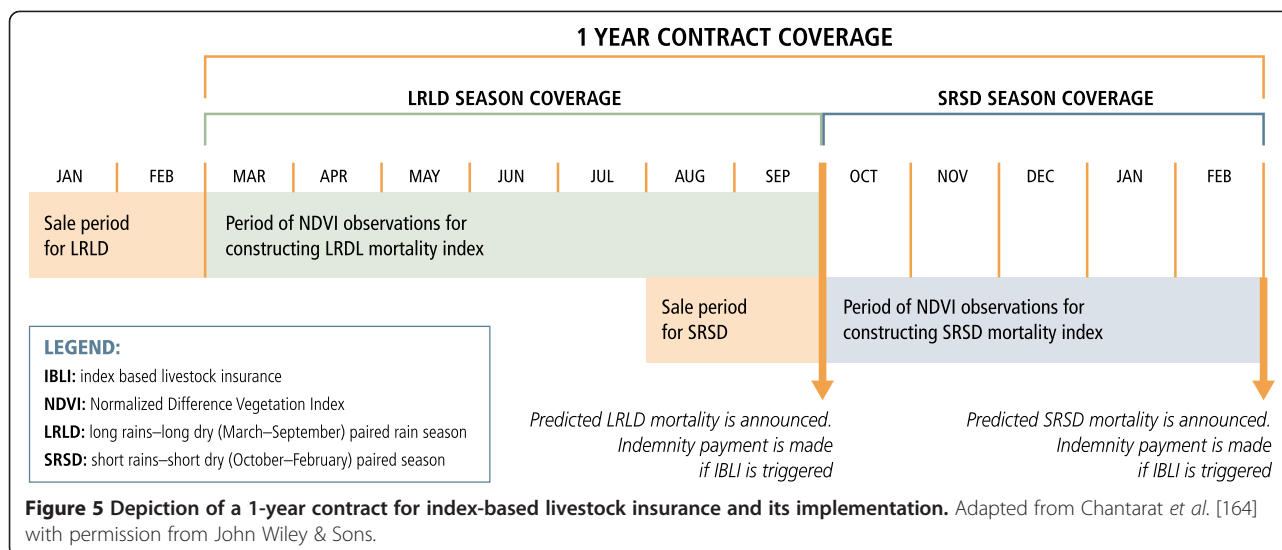
woven into climate change policies and programmes [151]. Key to this effort is linking science, technology and decision-making to the context of socioecological systems to better achieve balance between economic, cultural and social needs [152]. Systems that effectively leverage science and technology in support of sustainability efforts create salience, credibility and legitimacy across boundaries where boundaries exist between science and policy, disciplines, public and private sectors, and/or organizational hierarchies. Actions employed within these systems include convening (bringing all stakeholders in the CSA context together to foster communication and build trust), translation (defining a shared ontology and language), collaboration (actors working together to produce applied knowledge and specific outcomes, with specific mechanisms in place to facilitate interactions across multiple boundaries) and mediation. Specifically, mediation is 'a process by which different interests are represented and evaluated so that mutual gains can be crafted and value created in a way that leads to perceptions of fairness and procedural justice by multiple parties' [152], p. 470. These components, as well as broad stakeholder engagement from the initiation of a project, are keys for linking science with action, developing knowledge networks and forming critical capacity to reach desired outcomes also see [135-137,152]. Other approaches for forming new knowledge networks and adaptive capacity in the socioecological system combine both back-casting and explorative scenarios [137]. Interactions between climate change and culture, as well as ideas regarding the ethics and morality involved with climate change and the role of these constructs in stakeholders' and the larger society's adoption of actions related to mitigation and adaptation, are outside the scope of this article, but they are discussed by Hayward [153] and Markowitz and Shariff [154].

Climate risk management: financial mechanisms, insurance and climate services for farmers

An alternative to emergency aid in the face of climate shocks is reliable programmes developed to minimize farmer risk, which could prove to be more effective by preventing the slide into poverty traps [155]. The uncertainty of climate change, especially extreme events, makes it difficult for individual farmers to incorporate risk into their decision-making [156,157]. Vulnerabilities to climate effects on production, pests, disease and price volatility depend on farmers' assets and natural resource base [158]. Appropriate risk management tools, such as improved forecasts and extension support, and appropriately designed safety nets or insurance instruments must revolve around the vulnerabilities in specific farming situations. Rural households in developing countries, limited in both resources and access to information, could

be disproportionately affected unless appropriate measures are introduced to manage the additional risk and uncertainty related to climate change [159-161]. Innovative management of risk and uncertainty employs financial mechanisms (for example risk transfer or insurance contracts) that use several types of methods to understand investment decisions, technology choices, and risk perceptions. These methods include remote-sensing technology, micro-level household data, analysis of diversification, and farm surveys. Implementation of such insurance instruments requires appropriate technical innovation, building awareness and trust, ensuring viable market demand, and enhancing local capacity building among local financial institutions [162,163].

Index insurance is one such instrument that effectively reduces farmers' risk under a changing climate and generally has many advantages. With index insurance, indemnity payments are decoupled from actual crop losses, instead of linking payments to changes in attributes that impact or reflect crop growth or survival over a given spatial extent. This then reduces transaction costs associated with verifying ownership and losses, removes the opportunity for individuals to change their risk behaviours to increase the likelihood of receiving a payout, and allays the problem of adverse selection, in which high risk individuals are disproportionately represented in the insured pool. Most vitally, the rural poor are no longer widely excluded from insurance by the need to demonstrate assets as a prerequisite to purchasing a policy [161]. For example, the Index Based Livestock Insurance (IBLI) programme recently launched by The Index Insurance Innovation Initiative seeks to accurately represent the insured's loss experience through the use of landscape-level data derived from measures such as the Normalized Difference Vegetation Index (NDVI) (Figure 5). NDVI is a satellite-derived indicator of photosynthetic activity or a proxy for plant production to feed livestock, which is available in real time every 10 days [165]. Livestock in Northern Kenya's arid and semi-arid lands account for more than two-thirds of average income, with most livestock mortality associated with severe drought [164]. Herd losses that push a household below a certain threshold tend to result in long-term consequences, including destitution, which can trap the household in poverty. The data derived from the developed index showed that the NDVI performed well when tested against other herd mortality data from the same region, and, when compared to drought experiences over the past 27 years, removed 25% to 40% of total livestock mortality risk in simulations. The IBLI programme has been implemented, with initial payouts issued to households in October 2011 [166]. Actions needed to facilitate establishment of the IBLI include identification of systematic criteria for end users to evaluate whether they



need to purchase this insurance product [167] and development of programmes for client recruitment, low-cost marketing, and claim settlements.

To provide long-term farm and community security in support of CSA, bundling agronomic breeding programmes for drought tolerance and financial programmes with index-based drought insurance will maximize farms' resilience to financial shocks due to drought, especially as the drought tolerance of crops diminishes with more severe drought stress. Developing and planting crops with drought tolerance is primarily a more cost-effective risk management tool than index insurance in the face of less extreme climatic events; however, index insurance could complement both private and public crop improvement programmes by providing assistance when even drought-tolerant varieties fail during extreme climatic events. Demand for bundled strategies seems likely to be high [168,169], thus creating a sustainable market for both drought-tolerant varieties and index insurance. To assess how bundled strategies affect household welfare and operate in practice in a drought-prone region of Ecuador, Carter and Lybbert [170] estimated the underlying probability structure for traditional maize yields from yield data collected annually by the Ecuadorian government from random samples of producers in different regions of the country. The certainty equivalent of the drought-tolerant technology was 6% higher than that of traditional technology. Incomes were most stable under drought pressure when drought-tolerant and insurance index technologies were combined, but interactions of such bundled strategies with other risk management and safety net programmes remain to be determined.

Uncertainty influences individual farmers' expectations of yield and dramatically impacts their adaptation behaviour. For example, government policies to protect farmers

against climate-change risks, such as insurance programmes and direct *ex post facto* payments after extreme climate shocks, may reduce farmers' incentives to diversify farm production away from more climate-sensitive crops. Antón *et al.* [30,171] examined farmers' responses to agricultural risk management policies under conditions of climate change using a stochastic microeconomic simulation model calibrated with data derived from farming in Australia, Canada and Spain. They distinguished between farming risk and uncertainty with regard to climate and farmers' beliefs. They examined the impacts of *ex post facto* disaster payments and three types of crop insurance (individual yields, area-based yield and weather index) utilizing a combination of climate-change scenarios (no change, marginal change, change with an increase in extreme events) and farmers' behavioural response options (lack of adaptation due to misalignment of expectations, diversification, structural adaptation). Their model results indicated that farmers in Australia and Spain, in the absence of government policy, would respond by increasing diversification, assuming they correctly anticipated climate change. The introduction of risk management policies in these two countries tended to crowd out diversification, and this effect increased with climate change. The relative cost-effectiveness of policies depended strongly on the extent of extreme events and farmers' misperceptions of climate (that is, misalignment), which can greatly inflate a policy's budget. Reducing the uncertainty that farmers face, with regard to how climate change will affect them, by developing information strategies will aid in the design of robust risk management policies and will limit the excessive financial costs brought on by misperceptions [30].

The goal in using the risk management instruments described here is to promote resilience of rural households to weather shocks and climatic variability, a key

premise of CSA. Although not addressed here, other index insurance products promote the integration of rural households into market production and often are used in concert with programmes aimed at promoting agricultural value chains and supply chain risk management [162]. These kinds of programmes consolidate and facilitate the participation in the agricultural value chain by specific populations in discrete regions, and they are intended to help increase farmers' access to credit and to encourage investment in appropriate technology to increase productivity.

Energy and biofuels: development of production methods and technologies to cut emissions without interfering with food production

Bioenergy is the native energy resource embedded within agriculture, but, more fundamentally, agriculture is itself an energy conversion process with the capacity to develop a rich portfolio of products for diverse markets, including markets for food and energy. The role of biofuels in achieving reduction goals (that is, mitigation) for GHG emissions and meeting future energy needs (that is, adaptation), as well as their impact on food commodity prices, remains a principally global issue [172,173]. Estimates of increases in food and commodity prices suggest that between 3% and 70% of retail food price increases can be attributed to biofuels; however, this wide range stems from differences in time periods, data sets using different price series (export, import, wholesale, retail) and different food products [174-176]. Global models used to predict mid- to long-term effects of biofuel production growth on prospective prices, production of feedstocks (for example, maize, sugar cane, oilseeds), mitigation and adaptation measures, and land-use change are general or partial equilibrium (PE) models. General equilibrium models encompass supply, demand and prices in the entire economy and take into account multiple markets and associated inputs; PE models are focused on equilibrium conditions in an individual market or sector of a national economy, in which prices, quantities under demand and product supply remain constant. Along with models used to assess land-use change in response to bioenergy production [177] are models such as the Asia-Pacific integrated model, which is used for analysis of global and national CO₂ emissions, mitigation costs and C taxes [178]; the Modular Applied General Equilibrium Tool which is used to examine links between agricultural markets, the general economy and agricultural policy issues [179]; the Global Change Assessment Model, which is an integrated assessment model of energy, agriculture and climate used extensively by IPCC and others [180,181]; GLOBIOM, which is used in analysis of mid- to long-term land-use change scenarios in agriculture, forestry and bioenergy

[182]; and the Model of Agricultural Production and its Impact on the Environment which is utilized in evaluating spatially explicit patterns of production, land-use change and water use in different global regions and linking economic development with food and energy demand [183,184]. These models can provide information regarding uncertainties, costs and trade-offs crucial to CSA for (1) climate policymaking, GHG mitigation and sustainable energy futures and (2) projections regarding agriculture, agricultural markets and the future of the world's food and feed supplies. The case studies described here are used to assess costs and trade-offs of biofuel expansion at the farm and global scales as well as the impacts of enacted policies in the European Union (EU) and the State of California in the United States.

Increased future demands for food, fibre and fuels from biomass can only be met if the available land and water resources on a global scale are used and managed much more efficiently than they are now. Therefore, developers of an integrated bioenergy framework must incorporate not only bioenergy's mitigation potential but also its costs and trade-offs with food, water security and land use. To assess the cost-effectiveness of bioenergy for climate change mitigation, Popp *et al.* [184] coupled global models of vegetation and hydrology [185,186], land-use optimization (MAGPIE) and the energy–economy–climate interface [187]. If all suitable land for agricultural production was made available, bioenergy from specialized grassy and woody bioenergy crops, such as *Miscanthus* (poplar), could produce 100 EJ globally by 2055 and up to 300 EJ by 2095. However, bioenergy cropland would grow from 1.52 billion ha to 1.83 billion ha, thereby increasing CO₂ emissions due to deforestation. Meeting bioenergy needs while preserving intact and frontier forests would require higher rates of technological change in agriculture (by 0.9% per year until 2095), thus leading to additional costs. The potential trade-offs of conserving forests and cultivating bioenergy crops on a large scale include conflicts with respect to food supply, food prices (especially in the tropics) and water resource management [188].

In the EU, market demand for biofuels and biomass will likely increase as the region becomes less reliant on fossil fuels and the EU implements targets for renewable energy, such as the Renewable Energy Directive and the ensuing national renewable energy action plans. This demand was first met with imported biomass sources from residue streams, such as palm kernel shells and wood pellets, and industrially produced biomass, such as palm oil and ethanol [189]. In an analysis conducted for the International Energy Agency, Hoefnagels *et al.* estimated future intra- and inter-European trade of solid bioenergy biomass by combining geographic information system models of transport routes with models of supply and

demand for energy crops, forestry products and/or residues and agricultural residues [189]. They estimated that intra-European biomass trade could increase to 6,560 kilotonnes of oil equivalent (ktoe) by 2020 in the low-import scenario and to 5,640 ktoe in the high-import scenario. Transportation costs could contribute substantially to these totals (for example, up to 75% (9 €/GJ) of the total cost (12 €/GJ) in the case of forestry residues). However, they determined that the lower transportation costs of pelletized biomass would not make up for its high production costs. In both scenarios, the chief future exporting regions for inter-European biomass trade included Poland, Estonia, Hungary and Slovakia and the major importing regions included Germany, Italy, the United Kingdom and the Netherlands. Within the CSA strategy, these modelled outcomes can help in the identification of the issues and stakeholders that should be involved in the development of future energy use and policy.

Newly enacted low carbon fuel standard (LCFS) policies in California and the EU offer promising approaches to reducing the C footprint of transportation fuels. The LCFS applies to itself a direct life-cycle C intensity analysis that captures all GHGs emitted per unit of fuel energy during extraction, cultivation, land-use conversion, processing, transport and fuel use [190]. Both California's LCFS and the European Parliament's revised fuel-quality directive require a 10% reduction in GHG emissions by 2020, and both allow credit-trading. These standards differ from previous policies aimed at reducing petroleum fuels, which comprised volumetric mandates and only indirectly required reductions in GHG emissions. As a case in point, the US renewable fuels standard requires annual sales of 36 billion gallons of biofuels by 2022, 21 billion gallons of which must derive from advanced biofuels and achieve a 50% reduction from baseline life-cycle GHG emissions. The other 15 billion gallons must come from corn ethanol [190]. With this focus on total GHG emissions rather than on volume, biofuels under LCFS will not be forced into a small number of categories, and transformative innovation, a key part of the CSA strategy, will be promoted. The flexibility and performance-based nature of the LCFS allows industry, rather than government, to pick the likely biofuel winners [190]. If implemented on a global scale, such changes in biofuel policies will heavily influence agricultural markets and environmental outcomes. Tokgoz *et al.* [191] simulated a reduction in maize ethanol production of the magnitude suggested by the LCFS analysis by utilizing a modified version of the International Food Policy Research Institute's (IFPRI) PE model, or the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). IMPACT was developed to project future global food supply, demand and

security in 115 country regions. Holding biodiesel production levels constant at 2010 levels in this model dramatically decreased rapeseed and soybean oil prices and increased the availability of food calories. Building future international policies upon the LCFS policies implemented in Europe and California will further the demonstrated benefits of reducing fuel C intensity rather than promoting policies that benefit biofuel producers who pursue ongoing profit-driven growth.

Policymakers and financial institutions have been hesitant to invest in bioenergy, owing to negative press and the resultant uncertainty about its long-term sustainability. In response, the scientific community must present a balanced perspective of how bioenergy can (or cannot) be managed as part of CSA (for example, see [172,173]). Models comprising the global impacts of bioenergy, along with agricultural productivity at local, regional and country scales, can be utilized to effectively assess the realization of environmental and economic objectives via policy and technology [192]. Separate consideration of bioenergy in the agricultural context will lead to suboptimization of the system with the likelihood of realizing lower environmental and economic benefits [193]. The viability of biofuels will be achieved when their cost is competitive with those of fossil fuels when it includes both the cost of the feedstock seed and the value of co-products derived from the biofuel by-products, which can provide additional revenue. In some cases, large subsidies are required to make biofuels competitive with fossil fuels (for example, *Jatropha*-based oil in Senegal) and/or feedstock seeds must be imported to satisfy demand, suggesting that alternative feedstocks should be adopted [193]. A stable supply of feedstock, determination whether other industries strongly compete for the same feedstock and access to a well-functioning value chain for the product are all crucial to facilitating vertical integration of production, conversion and processing, as observed in Brazil's biofuel sector. Msangi and Evans [194] suggested that growing a biofuel feedstock that can serve as a food product with coproducts will create greater stability for the farmer and that solving problems of food security in developing countries will lead to a flourishing biofuel sector. Furthermore, increases in food crop production and efficiency underpin the success of increased reliance on bioenergy and the conservation of forested lands in lieu of expansion of agricultural lands [188]. Lignocellulosic biofuels also can be a strong component of GHG mitigation with small impacts on global food prices, especially if sufficient land for feedstock production exists and does not compete with land devoted to food production, as indicated by modelled outcomes [173]. It is imperative to engage producers and affiliated industries in research to better understand how markets for new development of bioenergy and

nontraditional biological products can become an integral part of energy-efficient agriculture.

Theme 2

Landscapes and regional issues: land use, ecosystem services and regional resilience

Recently, extensive research on climate impacts on landscape and regional scales has been stimulated in part by policies that require institutional action to mitigate and adapt to climate change [14,195]. Such research includes use of remote sensing to analyse land-use mosaics, inventory approaches to assessing C stocks and water resources, and models to examine the potential of land-use change in different climate scenarios [196-198]. These techniques are being combined with farm- and field-scale data on crop performance, soil biogeochemistry and irrigation use to analyse if and how mitigation and/or adaptation strategies build food security and ecosystem services [34,199-201]. Interdisciplinary science underpins an integrated landscape approach, along with involvement of stakeholders who hold key information for developing climate-change scenarios and innovation pathways [202,203]. Landscape approaches that expand beyond agriculture itself are needed to understand how extreme events trigger rural outmigration and create new types of rural-urban connections. The development of metrics and indicators to track responses of climate change and ecosystem services is accelerating with broader recognition of the need for greater accessibility of data, formation of more types of socioecological assessments [203-205] and charting of the progress of climate-change policies.

Climate change and food security: modelling adaptation and uncertainty

Determining the adaptive capacity of mitigation and adaptation scenarios that will evolve with CSA's participatory processes rely, in part, on biophysical models. Models that will be used to examine the limits to crop adaptation as well as the impacts of climate change on biodiversity, land use and ecosystem services are now available [2,206]. They still contain much uncertainty due to (1) the ability of process models to accurately simulate the growth and development of crops when exposed to very high temperatures and elevated CO₂ levels, (2) the rate and degree to which agricultural productivity and development can progress in concert with reductions in GHG emissions and (3) the ramifications of successful agricultural adaptation to climate change for land-use change and associated ecosystem services [207-209]. Despite these uncertainties, the use of models and scenario-building has led to the exploration of potential synergies and obstacles to coping strategies in agricultural that would not have been possible

with empirical data alone [210,211]. Here we present modelling approaches to evaluating adaptation scenarios across the EU, the Mediterranean region and the United States.

Modelling can be used to identify climate-change impacts and sensitivities as well as possible adaptation strategies. Rather than being focused solely on climate-change constructs, such vulnerability assessments also include changes in CO₂ concentrations, GHG emission management, N deposition, land use, and socioeconomic trends to manage vulnerability. The Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) program produced a new set of climate scenarios for Europe in multiple global change scenarios and ecosystem models [212]. A dialogue among relevant stakeholders from the private sector, governmental and nongovernmental organizations and policymakers was conducted. Unlike global trends, European trends included moderate or no population increase, little urbanization, increased forest area and decreasing demand for agricultural land. The modelled outcomes allowed for changes in land management that could decrease vulnerability, such as C sequestration due to reforestation. Modelled outcomes indicated that the Mediterranean region could face increased risks of forest fires, water shortages, changes in tree species distribution and losses of agricultural potential. Under the different scenarios, which ranged from business as usual to greatly reduced GHG emissions, 20% to 38% of the population in the Mediterranean would live in watersheds under stress and experience water scarcity exacerbated by increased tourism and demand for irrigation. Mountain regions would be especially vulnerable because of less snow cover and subsequent changes in river runoff. These modelled outcomes provide opportunities for back-casting and identification of sensitivities where mitigation and adaptation efforts should be focused, as well as how subsequent research could inform policies around such efforts.

The participants in the EU SmartSOIL project [213] employ a CSA-like strategy that includes stakeholder involvement and is used to examine the implications of findings for economics and policy implementation. As of 2012, consultation with policymakers and advisors had begun in six case study regions [214]. The creators of SmartSOIL developed a framework of C flows and stocks informed by new data and meta-analysis of long-term European experiments that are relevant to short- and long-term CSA management decisions. This framework will be used to improve existing soil and crop simulation models out of which a simplified model will be derived to predict scenarios for future management systems to improve productivity and enhance C sequestration. As an example of modelling for C sequestration, Lugato *et al.* [197] used the CENTURY model to inform proposed European policies on the mitigation potential

of agricultural soils through C sequestration and to assist in the evaluation of the agricultural sector's deployment of 'greening' measures for agriculture that benefit climate and environment as required in the EU's post-2013 Common Agricultural Policy. Nearly 16 soil-climate-land combinations in the EU and neighbouring countries (Serbia, Bosnia and Herzegovina, Croatia, Montenegro, Albania, former Yugoslav Republic of Macedonia and Norway) were used in calculations, including the main arable crops, orchards and pastures as well as management practices (for example, irrigation, mineral and organic fertilization, tillage) (nearly 164,000 scenarios). Testing modelled results against soil inventories collected using comprehensive and standardized approaches (the European Environment and Observation Network and the Land Use/Cover Statistical Area Frame Survey) strengthened the examination of the uncertainty of modelled outcomes. Consideration of a broad spatial extent (pan-EU scale) allowed for better evaluation of C sequestration, in which an estimated current stock of 17.63 Gt C is predicted to increase through 2100. Within the pan-EU region, stocks will diminish in the southern and eastern parts because of higher soil respiration, whereas these losses will be offset by increases in the central and northern regions due to increased CO₂ atmospheric concentration and favourable crop-growing conditions. Such survey and monitoring programmes support the need for further spatiotemporal analysis of climate trends and stakeholder dialogue in modelling efforts so that proposed adaptation strategies are relevant to economic and socioecological contexts such as local, national and EU-wide policies and regulations.

Many climate modelling studies are focused on yield variations in response to changes in mean climate conditions [215]; yet, this approach overlooks several key factors, such as the occurrence of extreme events in which variance is changing [216]. Empirical approaches that capture the effects of extreme temperatures can be used to more efficiently assess climate impacts and adaptation. For example, in Mediterranean sunflower and wheat, an increase in both mean temperatures and climate extremes modelled under A2 and B2 scenarios (year 2100 business-as-usual and reduced GHG emissions scenarios, respectively) would cause severe yield reductions by shortening growing seasons and intensifying heat stress [217]. In the United States, yield patterns of rainfed maize have been explained by accounting for extreme events using the process-based Agricultural Production Systems Simulator (APSIM). With APSIM, observed negative yield responses to extreme heat shocks (measured as accumulated extreme degree days) were best explained by increased vapour pressure deficit (VPD). VPD contributed to water stress by increasing plant demand for soil water and reducing future water supply as a

consequence of higher plant transpiration rates [218]. The ratio of water supply to demand, as modelled with APSIM, was three times more responsive to a 2°C mean warming than to a 20% reduction in rain. The results of these studies direct researchers, policymakers and extension agents to take science-based actions that rely on climate scenarios and predicted outcomes that are not based solely on the change in climatic means but include climate extremes. Despite incongruences between actual biological patterns and model simulations, model outputs provide an evolving information base for planning strategies and new research directions.

Quantitative assessments of adaptation to consider the effects of extreme events on agriculture can inform policymaking by providing a much wider set of outcomes than is possible with perceptions or projected impacts. Modelled outcomes evaluated in a socioecological context allow investigation into the limits of adaptation and related consequences for agricultural productivity, other economic sectors and land use (for example, an indicator-based, spatially explicit and scenario-driven adaptive capacity model [211]). Coordinated cycles of model improvement and projection across multiple spatial scales (global, regional, local) will facilitate model validation and calibration as well as effective use of studies with different geographical domains [219]. Challinor *et al.* [219] recommended that different model intercomparisons and improvement programmes (MIPs) form separate but linked strategies, that detailed modelling studies of response mechanisms (for example biophysical processes, crop yields) and robust experimental data (for example, see [208]) underpin the models and that systematic comparisons of impact studies and their outcomes be used to address sources of models' uncertainties. Involvement of stakeholders at the outset of model development also aids in development of relevant scenarios and tools [152]. Modelled outcomes form a key part of the climate policy and governance process necessary to attain the Copenhagen 2°C target, which requires 70% to 90% worldwide emission reduction targets and which has been questioned as being too weak [220]. A wider set of options for targets will be facilitated by examining options for climate governance (that is, institutional mechanisms to guide and direct societal policymaking) and their societal implications, as well as assessing the potential for success in achieving the target within existing political structures (for example, democracy, autocracy) [221,222]. For example, the 'mitigate for 2°C but adapt for 4°C' option implies that society will take steps to adapt to existing in a warmer world, but will maintain the goal of reaching the current 2°C target. This approach will diminish conflicts and trade-offs associated with the water-food-energy nexus. Yet, if it is perceived that the 2°C target is unattainable and investment is strongly

supportive of adaptation, then acceptance of even higher target values and a greater need for adaptation-related burden-sharing will be a consequence [221].

Soil carbon and achieving multifunctionality through mitigation and adaptation

Soil resource degradation has led to loss of functions and ecosystem services, such as water availability, water-holding capacity, C storage, mitigation of GHG emissions and sustained agricultural productivity [223,224]. Soil degradation limits resilience to climate change and extreme events, such as drought, and therefore impacts food security and augments susceptibility to poverty, especially in vulnerable regions such as Sub-Saharan Africa. Better understanding of the biophysical capacity of agricultural landscapes to act as C sinks through capture and storage of atmospheric CO₂ in soils and perennial vegetation leads to strategic design and operational management for both mitigation and adaptation actions [122,225]. Improving biophysical capacity for desired functions such as GHG mitigation, food production and maintenance of soil and ecosystem biodiversity is a form of ecological intensification and is enhanced within a multifunctional landscape. Ecological intensification builds resilience by leveraging ecological processes to increase outputs from agricultural lands to promote (provisioning supporting, and regulatory ecosystem services) and decrease dependence on external inputs [93]. Balancing trade-offs between the different types of services can be facilitated by assessing indicators such as soil organic C (SOC). Trade-off analysis can employ simulation methods and modelling tools (for example, the Agricultural Model Intercomparison and Improvement Project, known as AgMIP; see [9]) to evaluate existing and alternative agricultural systems, changes in market conditions affecting supply and demand, and related policies in relation to climate change. The negative trade-offs can be minimized when landscapes are managed to achieve multifunctionality objectives, such as by a diverse set of land-use types, each providing a different combination of services [31]. The case studies below are focused on tools for accounting for GHG emissions and soil C storage, processes to enhance soil C storage and use of a paired economic-biophysical model to assess impacts of mitigation efforts within multifunctional landscapes.

Climate-change mitigation and adaptation within multifunctional landscapes depends on the multiple roles of SOC, which include a reservoir for plant nutrients (N and P) to support crop production and reduce external inputs, a substrate for soil organisms affecting their activity and diversity, and a promoter of soil physical structure leading to enhanced water quality and reduced erosion [223]. To maximize mitigation efforts, accurate GHG calculation can engage stakeholders and other end users to

form a database with which to understand the C budget of their practices, such as SOC sequestration and storage and CO₂ emissions from fossil fuel combustion. Many models used to calculate GHG emissions and SOC are designed for specific geographical areas to meet distinct needs. Colomb *et al.* [226] provided information on the features of 18 available calculators and created a framework for choosing the most suitable GHG and C calculators for a given situation. They found that major sources of GHG emissions were usually well-identified, but that the calculators used failed to account for landscape effects due to land-use change. Few calculators accounted well for emissions from the loss of previous biomass, which is especially crucial in cases of deforestation–reforestation or rehabilitating and restoring grazed and ungrazed grasslands. To illustrate this point, Colomb *et al.* [226] used seven calculators to assess the GHG balance of replacing grassland by wheat, a case where the average emissions due to land-use change were greater than those that occurred during the production of wheat itself. Owing to differences in reporting units, measurement of emissions and scope, the results obtained with different calculators could not be directly compared and uncertainty levels were very high. Minimizing uncertainty in C and GHG accounting methods will provide reliable data to aid global markets and agencies for use in developing GHG- and C-footprinting and life-cycle assessment criteria. Greater standardization of metrics will also help in the enumeration of trade-offs in balancing between crop management and land use.

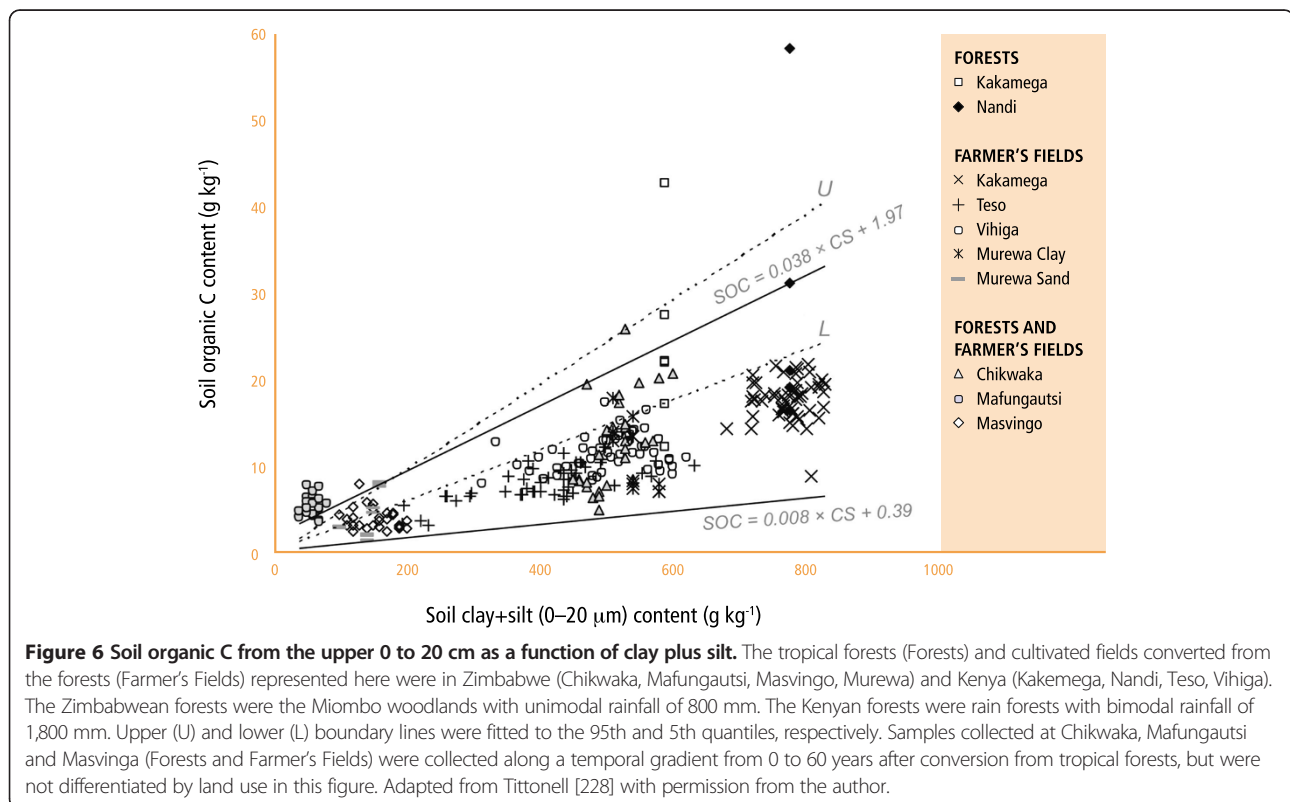
The design of multifunctional, ecologically intensive landscapes when providing ecosystem services of local and global interest is informed by analysing synergies between agricultural practices and landscape attributes [58]. For example, an analysis of carbon stocks and flows in smallholder farms in Kenya revealed positive synergies between agricultural production, on-farm biodiversity and above-ground C storage [227]. Dominant land-use types considered included home gardens, food-crop plots, cash-crop plots, pasture plots and woodlots. Close to the homestead, home gardens received the most organic nutrients in the form of compost, kitchen waste and manure, and downslope and farthest away maize, vegetables and eucalyptus woodlots were planted. Tree species diversity was highest in home gardens and near crop fields. Although such trees contributed up to 39% of total aboveground C storage, the greatest contribution came from monospecific woodlots dominated by *Eucalyptus saligna* (which contributed up to 81% of total aboveground farm C). In a landscape survey of 250 farms across 6 regions in Kenya, SOC, available P and exchangeable K⁺ varied widely but generally varied by management practice and reflected diminished soil fertility with greater distance from the homestead [58].

Thus, a combination of land-use practices contributed to C storage below and above ground as well as to multiple functions on the farm (Figure 6). Including the diverse agricultural landscapes in such studies leads to understanding of how management practices support ecological processes for C storage, and farmer participation supports identification of economically viable options for smallholder farmers [58].

Trade-offs between mitigation and adaptation occur often in agricultural systems, notably in the allocation of scarce resources between competing activities. The Trade-off Analysis model for Multi-Dimensional Impact Assessment is used to evaluate climate-change impacts and the viability of adaptation strategies by combining survey, experimental and modelling data [229]. Its next step is calculation of future land use, output, output price, cost of production and farm and household sizes for different climate-change and socioeconomic scenarios. The authors applied the model to the Vihiga and Machakos districts in Kenya to simulate changes in crop and livestock productivity and the effects of climate change to 2030. Climate change was projected to have a negative economic impact for 62% of farmers in Machakos and 76% in Vihiga, but these modelled effects could be partially offset by specific adaptation strategies. The most viable adaptation strategies included introduction of an improved maize variety or low-yielding,

dual-purpose sweet potatoes in Machakos and improved feed quantity and quality combined with livestock breeds adapted to increased drought and high temperatures in Vihiga. In some cases, mitigation activities result in negative trade-offs, such as organic practices that increase SOC offset net GHG emissions, leading to competition for feed for livestock or fuel, or even to decreases in average yields, thereby exacerbating forest conversion to agricultural land [122]. Agroforestry, however, contributes to multifunctional landscapes that support mitigation and adaptation and can lead to improvements in livelihoods, whereby provision of fuel wood, timber, fruits and/or fodder is often associated with the cobenefits of improved soil fertility, water infiltration and below- and above-ground C sequestration [40,150].

Currently, agricultural decision-makers and policy-makers rarely consider SOC to be a major factor in agricultural management or land-use change, and the concept of multifunctional landscapes is an emerging idea in the science-based policymaking realm. Yet, the study of SOC formation, its functions, its physical and chemical protection and identification of those fractions most susceptible to degradation is an area of active research. Through various international conventions, this scientific knowledge is slowly becoming part of the science–policymaking interface relevant to climate-change mitigation and adaptation (for example, the United Nations



Framework Convention on Climate Change, the United Nations Convention to Combat Desertification, and the Global Soil Partnership). However, the complex trade-offs in land-use decision-making regarding provision of multiple ecosystem services in a given landscape are usually local, so new interdisciplinary and socioecological research approaches are needed in order to down-scale information and options regarding how to best manage soil C in relation to other ecosystem services and farmers' livelihoods [40,122,150,230-232].

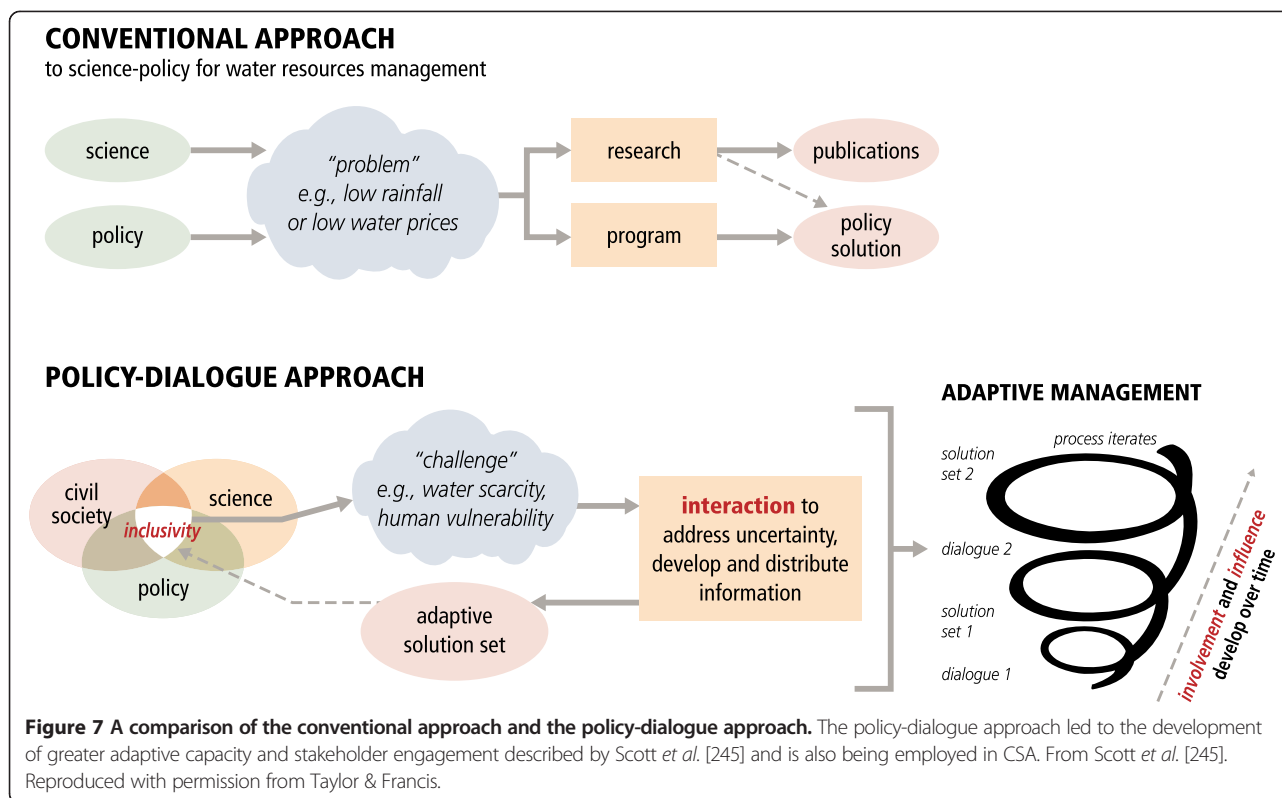
Water management for food and fishery systems

The effects of climate change on hydrology are far more uncertain than temperature change, and yet, global irrigation water demand will likely increase by approximately 10% by midcentury [233]. IFPRI models indicate that calorie availability in developing countries could potentially reach almost 85% of that in developed countries by 2050, but in more pessimistic scenarios, calorie availability will decline in all regions, due in part to lesser water availability [36]. IPCC models for irrigated areas within this same time frame indicate that the gap between potential evapotranspiration and effective rainfall will be about 17% by 2050 under a high-emission scenario, placing extra stress on demand for irrigation water [234]. Taylor *et al.* [235] asserted that land-use change may have even more noticeable impacts on the hydrological cycle than climate change itself, but that, given the strong focus of mitigation and adaptation planning on land-use change, the two will remain intimately linked. For example, following conversion of forests and grasslands to agriculture in the West African Sahel [236], Southeastern Australia [237], New Zealand [238] and Southwest USA [239], runoff and/or groundwater recharge increased up to two orders of magnitude. Such increases are not always sustained, owing to a range of vegetation cover and hydrological response factors [240]. Forests and woodland cover can also support water quality and, in some cases, can assist in reducing dryland salinization and water-quality decline in semiarid environments [241-243]. Massive abstraction of groundwater and redistribution to agricultural land (nearly 70% of global freshwater withdrawal and 90% of consumptive water use for irrigation) has led to groundwater depletion in regions with primarily groundwater-fed irrigation (for example, regions of China and in the Ogallala Aquifer region in the United States). With projected increases in drought incidence and severity, changes in rainfall patterns and intensification, and decreases in snowpack, agricultural areas that are currently irrigated with surface water will become heavily reliant on groundwater. In Mediterranean-type climate regions in California's Central Valley and in southern Europe, groundwater recharge will be highly dependent on uncertain changes in precipitation patterns

[235]. Aquifer salinization is also predicted to increase, at least in California's Central Valley [244]. Sea-level rise also threatens groundwater and surface water with saltwater inundation [245]. The case studies here depict adaptation measures that have been employed to meet the challenge of water management in the face of climate change across a range of spatial scales.

In the Central Valley of Chile, multidisciplinary teams have enacted a CSA-like strategy to address climate-related changes in water [245]. In Chile, farmers' permanent water rights are determined by estimates of minimum stream flow. In a high-emissions scenario, the Central Valley may experience temperature increases of 4°C by the end of this century [4], which would lead to decreases in water supply and thus challenge the existing system of determining water rights and their allocation. In the Maipo basin of Chile, snowmelt from the mountains will be reduced, affecting both river discharge and water demand. In a moderate climate-change scenario (B2), modelled reference evapotranspiration, an indicator metric of irrigation demand, was discovered to potentially increase by 10% to 15%, whereas under the high-emissions scenario (A2), increases ranged from 14% to almost 20% [31]. Permanent water rights vulnerability under the two scenarios, on the basis of data for monthly mean river flow and an agricultural census, indicated that water demands would be inadequately met in 40% to 50% of years under the more severe climate-change scenario. In response, farmers could change crops and/or cultivars, increase irrigation or sell their land and water rights. Even under current climatic conditions, farmers' existing water rights have been questioned because of increasing demand by urban users [245]. To address this issue of failing water rights and limited availability in future climate scenarios, a 'science-policy' strategy has been employed that involves civil society, scientists and policymakers in an iterative dialogue to identify the challenge and its solutions (Figure 7). Since 2008, annual meetings have been conducted with researchers and stakeholders from the national water service, irrigation commission, and environment ministry in Chile). The result has been increased inclusivity and quality of overall participation in topics such as climate-change impact assessment, water-allocation system reliability and water-sector adaptation evaluation, leading to improvements in decision-makers' support of studies on uncertainty in evaluating irrigation projects and future reservoir operations. The science-policy approach supports dissemination of information and projects to strengthen vulnerability assessment tools and coping strategies for irrigated agriculture.

In the Mekong River Delta in Vietnam, more than 700,000 ha of coastal habitats used for aquaculture are threatened by rising sea levels due to climate change.



Kam *et al.* [246] analysed the farm-level economic costs and benefits of several alternatives: (1) autonomous adaptation, that is, spontaneous adoption or response, to climate change; (2) no climate change; and (3) planned, or policy-driven, adaptive strategies in which costs are distributed more equitably across the supply chain or are borne by government and other entities. Here 'autonomous adaptation' includes farmers' responses to changes in land and water availability, commodity prices, market incentives, and climate variability. Such responses incur incremental capital costs and include using different levels and combinations of inputs, altering species and production systems, adjusting the height of pond dikes, and increasing water volumes pumped into ponds. Shrimp farmers will be better able to bear the cost of autonomous adaptation than catfish farmers because they sustain relatively higher profit margins and require lower capital investments than catfish farmers. However, without government intervention to prevent flooding and salinity intrusion, the shrimp industry in aggregate will likely experience higher adaptation costs, as it covers more area. Planned adaptive strategies include genetic improvement of breeding stock and pathogen control. Although constructing dikes would reduce river and coastal flooding and salinity intrusion in support of fish production (a provisioning service), opportunities for expansion in both brackish-water and mangrove aquaculture

systems that are key to coastal preservation (supporting service) will be lost. In general, evaluating adaptive planning with many types of metrics, including those for ecosystem services through restoration of coastal and intertidal vegetation, were found to provide more data to inform the final choices made by stakeholders [247].

Recently, the concept of rainbow water, or terrestrial and oceanic evaporation as a source of atmospheric moisture and subsequent precipitation, has emerged. This conceptualization frames how to harmonize the interests of all users of the hydrologic cycle [248]. Available blue water sources—water used for irrigation, industrial or domestic use—and grey water sources cannot support the rate of agricultural intensification, so interest in green water—rainfall used by forests and other vegetation—has grown. Although controversial, passage of air over vegetation with a specific leaf index of 1 in the 10 days preceding rainfall was observed to lead to increased precipitation in Africa [249]. It follows that assessments of climate must take into consideration whether, where and how landscape changes alter large-scale atmospheric circulation patterns of water far from where the land use and cover changes occur to avoid misalignment of investment in climate mitigation and adaptation [248].

Given that climate change is likely to reduce water availability across many agricultural regions, it is critical

that water policy and management practices focus on efficient and equitable water rights and allocation policies; increasing water productivity via more and better irrigation storage, conveyance and delivery systems that reduce evaporative losses; in-field water-use efficiency improvements; and technologies that reduce seawater intrusion in coastal environments. These challenges are equally important in the quest to increase agricultural productivity to feed a growing global population, irrespective of the degree of climate-change impact. Responses to the spatial and temporal shifts in water quantity and quality due to climate change involve many scales and stakeholders, and the need for coordinated planning at regional and national scales will increase with growth in the urban and industrial sectors. Approaches to increasing the efficiency of water used for food supply must employ drought-tolerant crops and irrigation technology (for example, water-conserving irrigation systems, crop coefficients and surface renewal [250,251]). They also need to address both consumptive behaviour (that is, overconsumption and resource-intensive food selection) and waste incurred during postharvest and along the supply chain (for example, threshing, transport, storage) [252]. Other adaptive strategies include the involvement of communities and government agencies in increasing storage capacity via small-scale reservoir projects, rainwater harvesting, groundwater banking through artificial and/or natural aquifer recharge and flood harvesting (that is, directed capture of floods in floodplains) and restoration of coastal vegetation to promote opportunities for aquaculture [242,244,252]. Additional adaptation options include reduction in end-user demand, deengineering and reoperation of water systems to create adequate supply and distribution, improved wastewater treatment plants to facilitate wastewater reuse, desalination plants and targeted water-conservation projects [253].

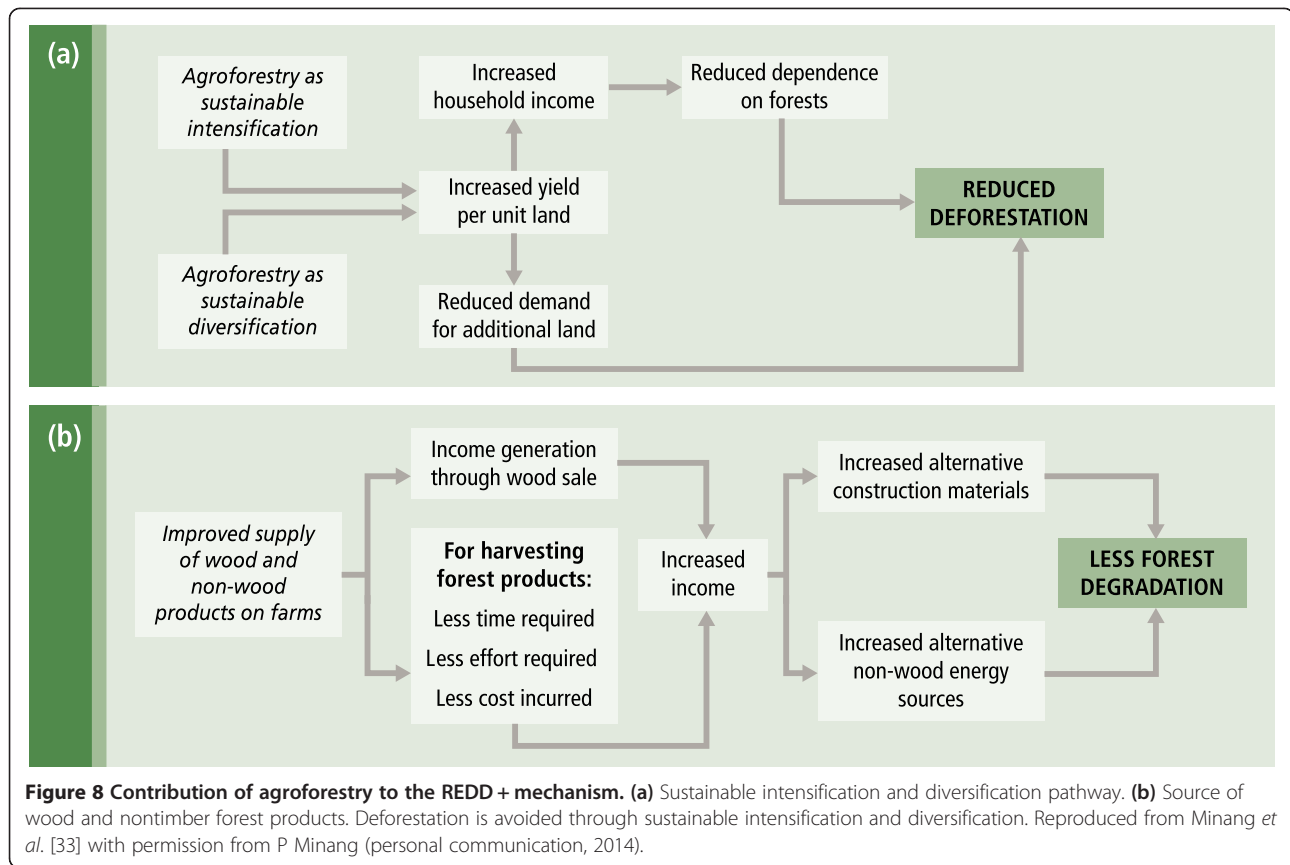
Managing forest biodiversity to increase ecosystem services and resilience

Forest loss and degradation cause GHG emissions and loss of C stocks, biodiversity and ecosystem services. Trees and forests buffer microclimates, regulate water quality and flows, store C and provide habitat for plants and animals in protected areas and corridors [248,254,255]. When landscapes are managed to contain a mosaic of forestry and agroforestry ecosystems, the diversification of food, feed and timber production, income sources, and markets promotes greater resilience to environmental uncertainty [149,256]. REDD + programmes to pay developing countries for conservation and sustainable use of forests have evolved over the past decade toward greater attention on (1) increased interactions between institutional networks and (2) achieving reduced

GHG emissions along with improvement of livelihoods of local communities and biodiversity conservation [257]. A systems approach involving biophysical and social sciences, as well as indigenous knowledge, is fundamental to demonstrating that REDD + projects are performance-based, fair and equitable [33]. Although afforestation and reforestation are often considered in REDD + projects, trees on farms are usually not included, owing to strict 'forest' definitions. Yet, agroforestry systems offer many REDD + -related benefits. Intentional integration of trees on farms and in agricultural landscapes increases C sequestration, along with greater food security and resilience [40,229] (for example, see Figure 8). Assessing such multifaceted trade-offs across an agricultural landscape is relevant to the CSA strategy, but will require greater coordination on local, regional and international levels to be incorporated into REDD +.

Examples of agroforestry types in agricultural landscapes include remnant forest or savanna, agroforests, tree crops, home gardens and boundary plantings [258]. Tree species and densities for each type are selected by desired ecological processes, farmers' criteria and land-use policies. An integrated landscape approach allows valuation of the ecosystem services derived from these management options and can be used to determine potential trajectories of tree-cover transitions [31,149]. It permits the nesting and spanning of spatial scales of different agroforestry types, the confrontation of biases for C benefits versus livelihood choices, and the optimization of tree-diversity exploration. It also opens opportunities to identify synergies and trade-offs and helps sidestep definitional challenges that result in negotiation platforms for proactive actions that reduce vulnerability and increase benefits (for example, see [259]). The landscape perspective is useful for scenario-building, such as comparing financial incentives that emphasize economic efficiency for agricultural and timber purposes versus socially 'green' and 'rights-based' approaches that support resilient livelihoods and broader sustainable development goals. The current scientific literature does not adequately detail these socioecological and community-based processes or how they underpin decision-making.

Examining trade-offs in REDD + can provide scientific information to enable science-based policies and decision-making, as well as coordination and standardization of REDD + practices. Many of the trade-offs involve livelihood issues that increase productivity and wealth, thereby encouraging land tenure and sustainable intensification through agroforestry. The results of household surveys and farm inventories have shown that agroforestry can help farmers deal with drought, flood and rain variability by reducing the need to sell land and livestock at low prices and instead sell seedlings, timber and firewood and consume tree fruit during the 'hunger gap' [33,40,260]. Sequestering



C on farms for climate-change mitigation will only be attractive to smallholders when short-term increases in income or welfare occur. Landscape models have shown the impacts of investing and implementing policy in ‘business-as-usual’ versus ‘green’ scenarios, such as allowing land swaps for permits granted within natural forest for oil palm expansion, so that plantations can expand only onto land that is already degraded, as well as tax concessions for plantations that expand only onto degraded land [261]. In a recent report, the International Union for the Conservation of Nature assessed climate-change mitigation activities across many regions of the world where REDD + policies likely would be implemented [262]. Examination of the social, economic and environmental trade-offs and potential synergies revealed that clear tenure and property rights, including rights of access, use and ownership, are essential for effective REDD + implementation To benefit local communities, including the most vulnerable, REDD + policies must enhance the ecosystem services upon which the rural poor are most dependent and leverage new financial resources to reward local communities for management. These opportunities can easily be lost if the vulnerable are explicitly excluded as beneficiaries (for example, because of unclear tenure) or high barriers to entry (for example, forest certification) [263].

Participatory, transparent, accountable governance can help achieve benefits of implementing REDD + policy by creating synergy between parties at multiple scales. A governance approach that facilitates harmonized goals and policies between civil society and engaged stakeholders focuses on the relationships among organizations rather than on new organizational structures and financing mechanisms. Public–private partnerships can improve the effectiveness of the biodiversity governance system and complement regional and multinational efforts [263]. In Cameroon, for example, nongovernmental organizations are implementing REDD + pilot projects and acting as bridges between the public and the state, both to create awareness among local communities and to voice concerns about social safeguards [264]. Such partnerships have helped government institutions organize international biodiversity governance around an ecosystem approach, largely by changing the scale and nature of the dialogue through a community of practice with institutions outside the immediate REDD + network [257].

Although REDD + will benefit from institutional interactions that build trust and reach eventual consensus on forming, coordinating and integrating policies that support livelihoods and resilience while sequestering C in forests, the definition of appropriate ecosystems for

payments still is a major issue. As pointed out by Visseren-Hamakers and Verkooijen [257], it remains to be seen whether CSA, with its integrated planning of land, agriculture, forests, fisheries and water, will be included in policymaking steps towards broadening of the REDD + agenda.

Rural migration due to climate change

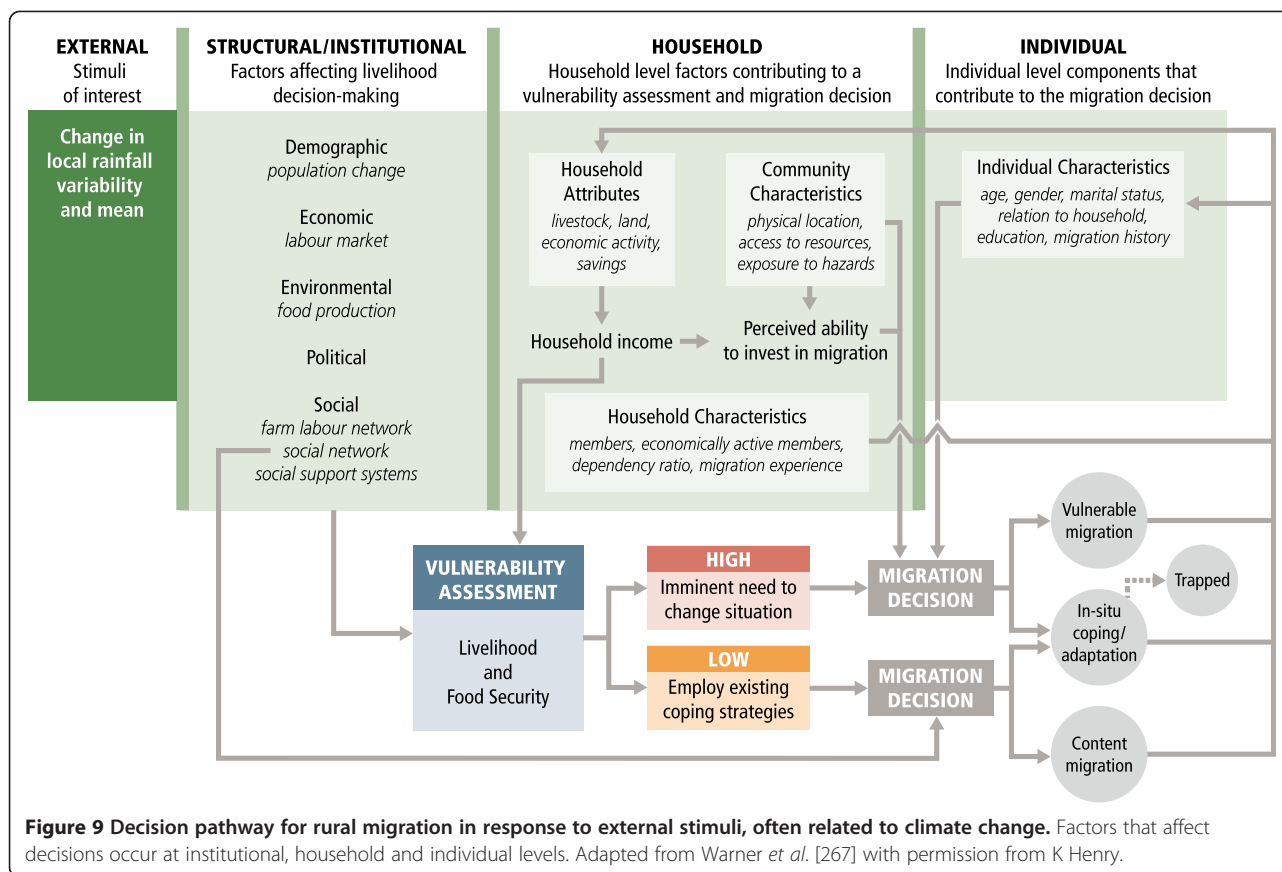
A worldwide transition toward urbanization is occurring, partly in response to climate change, although rural out-migration due to climate shocks, such as hurricanes, is better documented than gradual changes, such as lower rainfall in arid areas [43]. Migration within countries is complex, having both positive and negative impacts on adaptation and household resilience. Climate shocks and disasters can propel people living under vulnerable conditions into poverty traps that force migration out of rural areas [265], where men most often migrate, leaving the women and children with increased household and farming burdens [45]. Migration can be a beneficial strategy that spreads risks through resource diversification, such as remittances that bring money back to the household [266]. Livelihood and food security, as well as culture, affect who migrates, when, for what reasons and to which destinations [267] (Figure 9). Despite the material benefits that can result from mobility and migration, displacement of people from places that they value reduces culturally based activities, such as preplanning for specific climate-change events [42]. Migration can lead to inhabiting vulnerable urban locations, such as flood-prone areas [268], and increase inequities due to poverty and lack of social networks. Opportunities exist to improve structural and institutional frameworks to reduce migration from rural areas, including greater diversification of rural livelihood systems [149,269]; opportunities for public health, social equity and environmental welfare [270]; and connection of urban populations with local or regional food sources to support rural incomes [3,11,28].

Land scarcity and degradation are conducive to out-migration. In Guatemala, people from households affected by flooding or soil degradation were found to be more likely to leave settled rural areas for the forest frontier to engage in clearing of forests for agriculture [271]. Surprisingly, on the basis of employing a remote-sensing approach across Central and South America over a 10-year period, rural–urban migration was not observed to strongly affect the recovery of forest vegetation [272]. The researchers in that study found that a significant increase in woody vegetation occurred in only about half of the municipalities that lost population. Thus, depopulation does not necessarily imply land-use change. In their analysis of annual satellite land cover maps, they found that 180,000 km² of forest was lost

between 2001 and 2010, with the majority of deforestation occurring in South America (92%), particularly in Argentina, Brazil, Bolivia and Paraguay. Much of this land is in soybean production and cattle-grazing to meet the increasing global demand for meat. DeFries *et al.* [273] recently demonstrated that increases in rates of deforestation are closely linked to increases in urban populations and their demand for agricultural products rather than changes in rural populations. In Central America, temporary international migration of members of smallholder households has been indirectly associated with a lack of reforestation; remittances are spent on owning more land, and less household labour favours a transition to cattle production. This is relatively safe and risk-averse compared to row crop production, but it increases forest loss and land degradation and thus decreases the mitigation and adaptation potential [274].

Rural–rural migration offers a livelihood adaptation strategy for rural people facing stresses and shocks due to climate change, but it can also increase migrants' vulnerability. In Vietnam, migrants to the fertile Central Highlands aim to increase their economic livelihoods by producing coffee destined for international markets. Instead of settling permanently, many circulate between their new and origin communities because their social networks that remain at home allow them to avoid some of the risks of permanent relocation [275]. For example, family members in the community of origin may look after the migrants' children, take care of land and assets and provide access to loans. The lack of formal credit institutions at the new destination means that the community of origin may provide continual financial support instead of successful migrants' sending remittances home. Such social networks expose remaining household members to risk if ventures fail because of economic, social and environmental conditions. Both the migrants and origin households may then require loans to take further livelihood risks. In these cases, migration may drive both households into further poverty. Reforming Vietnam's household registration system to allow migrants access to banking, lending and other public services at their new locations could reduce the risks of such outcomes [275].

In the project 'Where the Rain Falls: Climate Change, Food and Livelihood Security, and Migration', researchers have examined rainfall, food security and human migration in eight countries in Asia, Africa and Latin America [267], mainly in agricultural areas. Four distinct household migration profiles were identified, varying along a spectrum from resilience, where migration is one of a variety of adaptation measures that progressively reduce climate sensitivity, to vulnerability, where migration either is difficult or exacerbates sensitivity to climatic stressors. Although national and regional contexts affect migration, household characteristics were discovered to be most



important for migration-related decisions and outcomes. For example, migration was generally erosive for the poor and those with small land holdings. Household size and composition, land ownership, asset base, degree of livelihood diversity and education levels were associated with migration strategies that increased resilience, such as non-agricultural jobs or diversified livelihoods [267]. One of the ‘Where the Rain Falls’ project case studies is the Mantaro Basin of Peru, where pressures to migrate stem from lower precipitation that reduced farmer and herder incomes [276]. Two livelihood and migration profiles in the Mantaro Basin were identified in response to climatic vulnerability. Lowland farmers who often commuted on a daily basis for casual urban employment used their proximity to the city to diversify their livelihoods. In contrast, herders farther from the city were forced to migrate for longer periods or permanently, in the absence of other options, and therefore were generally more vulnerable.

The act of migration has a risk dimension, whether it is a positive form of adaptation or part of erosive coping strategies. Understanding the cultural dimensions of risk-taking under climate uncertainty is crucial for determining migration decisions, especially as the necessity for climate-driven planned resettlement becomes more urgent [42]. Although outmigrants are mainly men, the

outcomes of climate-change-induced migration are likely to be highly gendered because women are disproportionately affected. Women tend to be poorer and less educated and to have lower health status and limited direct access to, or ownership of, natural resources [45]. It will become more feasible to identify risk-prone agricultural areas and circumstances if models of biophysical aspects of climate change and land use also take into consideration factors that influence migration decisions, such as landlessness, land tenure and distribution issues, as well as the role of social networks that facilitate resilience and adaptation in rural areas as well as escape from poverty traps [167]. Climate-induced outmigration from rural areas involves mitigation and adaptation issues related to urban and peri-urban outcomes, such as increased GHG emissions due to urban sprawl on land that once supported food production [11]. Interdisciplinary work is needed to understand effective strategies for developing and preserving small-holder agriculture near cities, expanding urban and periurban agriculture, managing urban growth for farmland preservation, connecting agricultural producers with local urban markets, ensuring availability of agricultural labour and enabling diversified rural livelihood systems. Such strategies will have combined benefits for climate change mitigation and adaptation.

Metrics for vulnerability assessment, food security and ecosystem services in agricultural landscapes

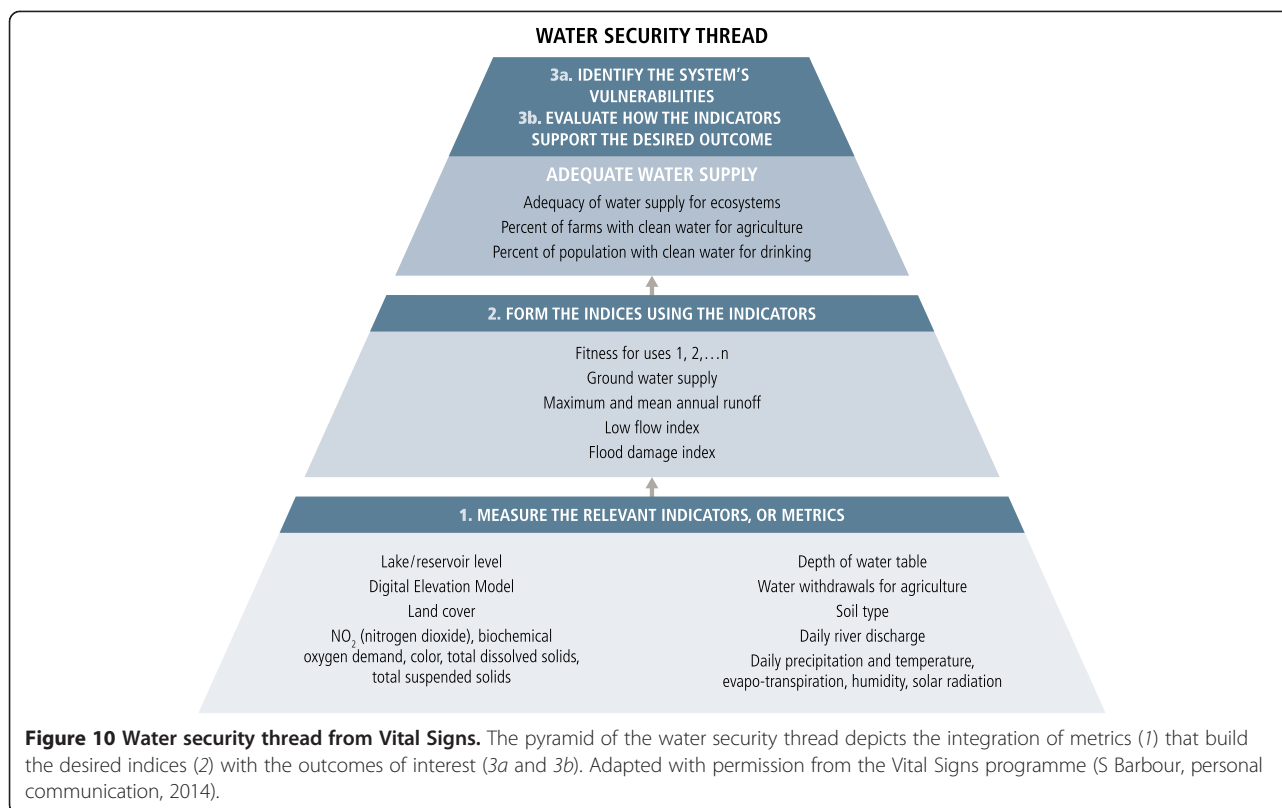
Science-based actions within CSA require integrated data sets and sound metrics for testing hypotheses about feedback regarding climate, weather data products and agricultural productivity, such as the nonlinearity of temperature effects on crop yield [277], and the assessment of trade-offs and synergies that arise from different agricultural intensification strategies. Approaches range from the development of broad indicators for identifying differences in climate vulnerability over large spatial scales down to the use of finely disaggregated spatial metrics [278]. New and innovative research and policy designs, as well as cooperative arrangements among and between government agencies, research institutions and civil society, have the potential to implement monitoring and assessment systems for decision-making. Examples presented here demonstrate how biometeorological, economic and sociological indicators can be used in vulnerability assessments and show nuances that must be addressed with respect to scale.

Novel outcomes, such as nonlinear effects of climate change on agricultural productivity (for example, US maize), are emerging based on the use of large-scale data sets, indicating that environmental change may drive agricultural productivity in unexpected ways [277]. For example, Lobell *et al.* [5] examined harvest and daily weather data derived from more than 20,000 historical maize trials conducted by the International Maize and Wheat Improvement Center and private seed companies in Sub-Saharan Africa from 1999 to 2007. 'Optimal management' and 'drought stress' were the two most common scenarios under which maize was grown. Final yield was reduced to the following different extents due to warmer temperatures: by 1% under optimal rain-fed conditions and 1.7% under drought conditions for every degree day spent above 30°C. Lobell *et al.* [5] suggested that a 1°C warming would lead to negative yield where maize is presently grown under optimal management (roughly 65% of the area) in Sub-Saharan Africa, whereas all areas in this region would show decreased yield of as much as 20% under drought stress. Similarly, in the United States, which generates 40% of global maize production, predicted increases in interannual weather variability (temperature and precipitation) could result in an 18% decrease in maize yields by 2030 to 2050 in comparison to the period from 1980 to 2000, along with increasing volatility in annual yields [279]. Expansion of cropland in other regions and retention of speculative inventories (that is, holding volumes for higher price earnings) may offset the volatility. Here metrics of climate and indicators of crop productivity and other agronomic factors predicted crop response to climate warming and drought over a widespread region, setting the stage for more research on

how adaptation measures, such as improving soil moisture and breeding for drought and heat tolerance, could be used to reduce vulnerability in the future [5].

Metrics that incorporate human ecology are integral to enabling the CSA strategy. Vital Signs [280] is a monitoring programme for changes in human well-being, agriculture and ecosystem services and is designed to provide metrics in rapidly expanding and intensifying agricultural landscapes in Africa, leading to integrated approaches that support food security (Figure 10). A primary goal of Vital Signs is characterizing the uncertainty and quantifying the sampling intensity needed to achieve different levels of accuracy and statistical power to detect change. Information gathered in the initial phase will be further evaluated for its overall utility and delivery cost. Measurements collected by Vital Signs participants are based on hierarchical spatial scales to provide integrated information that can inform structural relationships and counterfactuals involved in decision-making from the global to household scale. The global perspective facilitates comparisons between different regions ($250,000 \text{ km}^2 \cdot \text{region}^{-1}$), whereas regional measurements deliver information at the scale on which agricultural investments are made. Information collected at the landscape scale (10 to 20 units per region) measures the relationships between agricultural intensification, water availability, soil health and other ecosystem services, together with human well-being. Plot-level (1 ha) data reflect agricultural production, including seed selection, fertilizer type and application rate, as well as crop yield response. At the household level, surveys are employed to collect information on health, nutritional status, income and assets. Stakeholder planning meetings and participatory research established both at the onset and throughout the project are integral to garnering active engagement in Vital Signs.

Prioritizing allocation of resources and focusing policies on vulnerable regions requires metrics to assess susceptibility to a lack of food security due to climate change [281]. Biophysical climate indicators derived from global climate-change models and food insecurity indicators (that is, availability, access and utilization) can serve as such metrics. As an example of this approach, Ericksen *et al.* evaluated hotspots of vulnerability using the overlap among indicators of global climate (for example, rainfall variability, number of reliable growing degree days, and change in mean annual temperature) and food security indicators across the global tropics [281]. The latter were composed of availability (for example, crop yield and mean food production indices), access (for example, GDP per capita, transport time to markets, and monthly staple food prices) and utilization (for example, malnutrition prevalence and proportion of the population using unimproved water source). Future



vulnerability was depicted by existing resource pressure (for example, annual population growth and agricultural area per capita). The resulting index of vulnerability reflected three central components: exposure of populations to the impacts of climate change, sensitivity of food systems to these impacts and coping capacity of populations to address these impacts. With this vulnerability index, it was possible to rank the most highly exposed regions, leading to the emergence of southern Africa as a highly exposed region, as well as areas within Brazil, Mexico, Pakistan, India and Afghanistan. This approach is limited by the following factors: The data represent only current food security levels; data are gathered only at the national level, which masks variability within regions and among households; and other data are needed on climate-change exposure and on food security variables other than crop yields and utilization, such as food distribution and equity.

Systems delivering real-time indicators and metrics that are tied closely to management decisions and current conditions allow science and policymaking entities to progress from using lagging indicators to finding leading indicators that can be used to identify when and where thresholds of climate-change responses will occur [112]. Indicators and metrics are often used to support public goods and services, so better standards and codified practices that support shared vocabulary and ontology will

reduce the costs and streamline efforts for curating and disseminating such information. Research designed to develop metrics that inform global to local social networks for data collection, sharing and integration can also be leveraged for extension efforts. The identification of efficient and location- and situation-specific sets of indicators will complement efforts to construct human capital, social awareness and consensus regarding specific issues, leading to action strategies and policy guidelines across various temporal and spatial scales.

Theme 3

Integrative and transformative institutional and policy issues: bridging across scales

Figures 11 and 12 provide an overview of some of the main points covered in each session of the 2013 Global Science Conference on Climate-Smart Agriculture. The relative emphasis on mitigation of GHG emissions versus adaptive capacity to climate change (or both) varied depending on the session topic. CSA strives for food security, adaptation, mitigation and resilience, but not all of these are achieved in the same context. The session topics often invoked multiple scientific disciplines to inform further action and problem-solving strategies in support of CSA goals in the context of the session topic, but further integration across these topics and disciplines is necessary. Scientific uncertainties are inherent in climate science,

SESSION CONTENT FROM THEME 1 (2.0): FARM AND FOOD SYSTEM ISSUES: SUSTAINABLE INTENSIFICATION, AGRO-ECOSYSTEM MANAGEMENT, AND FOOD SYSTEMS					
Mitigation and/or adaptation	Interdisciplinary science	Scientific uncertainties	Social controversies	Stakeholder programs mentioned	Social-ecological pathways
2.1 CROP PHYSIOLOGY & GENETICS					
Mainly adaptation	Molecular biology, ecophysiology, agronomy	Plant response to high [CO ₂] + high temperatures	Genetic engineering	Regional crop breeding networks	Participatory plant breeding
2.2 LIVESTOCK MANAGEMENT & ANIMAL HEALTH					
Both	Animal science, range science, veterinary medicine, economics	Feasibility of scaling up of combined mitigation and adaptation strategies	Emphasis on low GHG emissions under poverty	Global programs for REDD+; for managing diseases	Management decisions based on livelihood criteria
2.3 NITROGEN MANAGEMENT					
Both	Agronomy, plant nutrition biogeochemistry	Decision-support tools effective across agroecosystems	Emphasis on low GHG emissions under poverty	Agricultural extension programs	Knowledge systems to enhance adoption of practices
2.4 FARMER DECISION MAKING					
Both	Social & political sciences, agronomy	Overcoming barriers to adoption of new practices	Dealing with perceptions of low climate risk	Social networks in farming communities	Short- & long-term planning for uncertainty
2.5 CLIMATE RISK MANAGEMENT					
Adaptation	Economics, remote-sensing, agronomy	Design of safety nets for uncertain climate shocks	Insurance reduces incentives for adaptation	Index-based livestock insurance programs	Bundled strategies for household welfare
2.6 ENERGY & BIOFUELS					
Mainly mitigation	Biogeochemistry, life-cycle analysis, agronomy, economics, geography	Projections of costs & benefits from biofuels	Food price increase attributed to biofuels	Energy directives and action plans	Biofuel feedstock value chains that support food security

Figure 11 Conference session 2.0 content within theme 1. Farm and food system issues: sustainable intensification, agroecosystem management and food systems^a. ^aGHG, Greenhouse gas; REDD+, Reducing Emissions from Deforestation and Forest Degradation.

given the difficulty of forecasting climate and its interactions with other aspects of human-induced environmental change. The examples that are mentioned here require intensified scientific activity, formation of knowledge networks, and involvement of many relevant stakeholders to obtain better information to support decision-making (see also [135-137,152]). Also, there are clear social controversies challenging CSA, often derived from assumptions and questions of equity and legitimacy, such as who will implement a response to climate change and how this will occur. To obtain buy-in from vulnerable populations and countries, such issues must gain the forefront in discussions of CSA science and policy among the diverse set of stakeholders described in the Introduction section above. Many of the stakeholder-driven programmes mentioned in the conference sessions exist at regional and global levels, as climate science is often funded for large-scale initiatives. As stated previously, this article and the conference presentations do not emphasize the local knowledge-to-action processes

that are essential for transformations towards climate preparedness. Nonetheless, some of the possible pathways towards such socioecological approaches to fostering greater participation and advancement of CSA objectives are shown for each of the session topics. Clearly, science must play an active and central role in developing the information base that will support food security, adaptation and mitigation in CSA and new types of inclusive, participatory decision-making as well as knowledge exchange processes [135,152].

Inter- and transdisciplinary scientific approaches are principal both to our understanding of how socioecological systems support the adaptive management and governance that are essential to long-term human provisioning of food and to the establishment of science-policy dialogues to plan for the future [47,282-284]. These actions are keys to assessing trade-offs of mitigation in context-specific situations, such that resource-poor farmers are supported rather than undermined by CSA. To realize the CSA objectives of increased food security,

SESSION CONTENT FROM THEME 2 (3.0): LANDSCAPE AND REGIONAL ISSUES: LAND USE, ECOSYSTEM SERVICES AND REGIONAL RESILIENCE					
Mitigation and/or adaptation	Interdisciplinary science	Scientific uncertainties	Social controversies	Stakeholder programs mentioned	Social-ecological pathways
3.1 CLIMATE CHANGE & FOOD SECURITY					
Adaptation	Agroecology, soil science, land use & geography, political science	Ability of models to simulate multiple types of processes	*Mitigate for 2 °C but adapt for 4 °C	Policy makers	Strategize with spatial/temporal modeling & stakeholder dialog
3.2 SOIL CARBON					
Both	Soil science, soil microbiology, biogeochemistry, agroecology	Accurate models of C, GHG emissions & tradeoffs	Support to create multifunctional landscapes	Science-policy interface of UN conventions	Participatory research across landscapes
3.3 WATER MANAGEMENT					
Mainly adaptation	Hydrology, land use & geography, atmospheric science, economics	Forecasting future water availability and demand	Governance, e.g. failing water rights, access & storage	Regional civil society & policy makers	Multi-stakeholder dialog for vulnerability and adaptation scenarios
3.4 MANAGING FOREST BIODIVERSITY					
Both	Forestry, agroecology, land use & geography, economics, political science	Appropriate methods & ecosystems for payments & rewards	Excluding the vulnerable as beneficiaries of REDD+	Multi-scale & multi-institutional planning for REDD+	Public-private partnerships for socially 'green' & 'rights-based' approaches
3.5 RURAL MIGRATION					
Adaptation	Social and political sciences, land use & geography, economics	Quantifying impact of climate shocks on out-migration	Disproportionate adverse effects on women and children	Stakeholder participation not clearly identified	Social networks that provide income, ties to the land & resilience
3.6 METRICS FOR VULNERABILITY					
Both	Ecology, social sciences, remote-sensing, land use & geography, economics	Biophysical & social data at scales that detect climate effects	Choice of indicators to direct policy decisions	Government and policy makers	Stakeholder involvement in data collection & for use of metrics

Figure 12 Conference session 3.0 content from theme 2. Landscape and regional issues: land use, ecosystem services and regional resilience^a.
^aGHG, Greenhouse gas; REDD+, Reducing Emissions from Deforestation and Forest Degradation.

resilience, mitigation and adaptation, scientific research supports awareness, analytical capacity and the evidence base to understand the impacts of climate change on agricultural growth strategies and food security, and identify climate smart options suitable to the local context [15]. How does research better inform the institutional, financial and knowledge-sharing arrangements to create a sense of possibility for transformative processes that reduce vulnerability and increases climate preparedness? Truly transformative solutions tap into a sense of possibility for positive action, and, as in business value propositions, there is a promise of goods and services to be delivered and experienced [47]. Yet, a 'doomsday' attitude has permeated much of the agricultural science regarding climate change, emphasizing harsh potential impacts under business-as-usual scenarios (Figure 2). Although it is effective in stimulating awareness and action in some sectors, CSA research is potentially more conducive to achieving food security, adaptation, mitigation and resilience. Examples include models that go beyond impacts to include adaptation and

transformation at either the farm or landscape scale (for example, see [211]), capacity approaches to examine multifunctional solutions within the socioecological system and direct evidence for situations, options and scenarios which increase human behaviours that build natural capital and resilience. Action-oriented research can also show how public-private partnerships can be used successfully to develop technologies, policies and approaches that may lead to sustainable food production and consumption patterns in a changing climate.

Uncertainty is one of the most difficult obstacles to determining priorities for CSA research. Not only is future climate uncertain, but so also is the existence and operation of the institutions that are and will be involved in adaptation, mitigation and resilience. Uncertainty can breed scepticism about the urgency to plan for climate change, especially in agricultural communities and industries that already deal with large annual variability in production and prices. Thus, uncertainty is a barrier to mitigation and adaptation among some of the stakeholders

whose investment, engagement and broad agricultural knowledge are critical for designing better research on coping strategies. CSA recognizes that the unfolding of decision-making processes, their translation into action and the formation of adaptive capacity depend on the socioecological contexts in which farmers are embedded (for example, the vital role of social networks in rural communities) (Figure 1). The ways of addressing uncertainty are likely to differ greatly among communities and socioecological systems, and research is needed to understand how to approach uncertainty in different contexts.

Although poverty can sometimes drive collective action, such as for improved food security in Kenya and Uganda through risk-sharing and pooling of labour and other limited assets [16], the least food-secure may be less likely to adopt new CSA practices because innovation implies additional costs before benefits can be realized [285]. Research on adoption of new farming technology and practices is needed to understand how upfront costs, lost income, worries about personal health and additional risks assumed during the conversion period can present formidable barriers to farmers [149], even if the new practices leverage ecological processes to improve sustainability and production [14]. For instance, diffusion of new germplasm with specialized traits (for example, drought tolerance) to targeted end users may suffer slow adoption even though new regional and local cultivars will likely be adapted to the range of conditions and management practices employed during climate change. To illustrate this point, modelled diffusion of a drought-tolerant variety among vulnerable (highly risk averse) farmers took four times longer than it did among those less vulnerable (less risk averse), underscoring the need for consideration of how seed prices affect the access of vulnerable farmers to new crop varieties [286]. Synthesis of information on how CSA practices have been facilitated by specific policy interventions, leading to broad community support, also is needed. A better understanding of how social benefits such as access to food and healthcare, rights to land and water, markets, and financing situations facilitate adoption of new farming practices or technologies will inform governance decisions [14].

Collective action for climate preparedness and problem-solving has already been effective in some situations. Safety nets for the poorest and most vulnerable households usually occur in the form of humanitarian relief and food aid, cash payments, agricultural inputs and public works [14], often after a critical event has occurred. Instead, communities can collectively plan safety-net strategies and resource transfers that are predictable and flexible enough to be scaled up and then scaled down when the crisis subsides [13,14]. CSA research on learning, knowledge-sharing and social network analysis can

help build awareness, early-warning indicators and criteria for benefit transfers for disaster responses and also effectively combine local collective action with national and/or international aid. Enhancing human and social capital, such as for childhood nutrition, entrepreneurship by women, and synergies between fuel use and C sequestration in trees, also rehabilitates household and community assets. Proactive planning will be more effective than reactive responses to a disastrous climate event, and research can help increase understanding of how adaptation policies must be designed accordingly [204].

Furthermore, collective action at the institutional scale is essential to avoiding conflicts that result from climate change. For example, institutional transboundary water agreements are associated with lower risk of conflict during water scarcity, but even one weak link in the communication, coordination and cooperation between coriparian nations will reduce their adaptive capacity to respond to new changes in hydrology, thus increasing the potential for risk and disputes [206]. So far, climate change has rarely been incorporated into such agreements. Collective action at the institutional scale could also address changing migration patterns of rural–urban connections that are likely due to extreme climate events and climate change and which will have potentially large ramifications on food production and food security, land tenure and cultural integrity [42] (Figure 10). At this point, research is needed to better understand how climate affects the dynamics of the rural labour force and thus on the stability of local food production for rural communities and nearby cities [267,287].

To realize CSA, research on targeted financing is essential, especially in support of the most vulnerable. Upfront investment to plan and start implementation strategies is required, as is research to develop monitoring systems designed to track climate-related human responses by utilizing consistent metrics that demonstrate private benefits along with public goods (for example, GHG mitigation). Already existent funds, such as the Adaptation Fund established under the Kyoto Protocol [288], and the International Fund for Agricultural Development's Adaptation for Smallholder Agriculture Program [289], can improve smallholders' access to climate-smart assessments, technologies and institutions related to sustainable management of forests, providing up to 16 million additional jobs globally and increasing household income in rural areas as a result of restoring degraded forest [290]. Larger-scale investments, such as financing infrastructure for water resources and carbon capture, can potentially be provided by the Green Climate Fund [291], and private finance may also play a role. As climate finance develops, research shares a role in prioritizing investments and effective financing solutions and in monitoring outcomes.

Investment in research on food systems that are resilient to climate shocks may be more likely to occur if CSA expands beyond the agricultural sector. As examples, CSA research could more explicitly involve issues related to: (1) local, national and regional food trade, including governance and regulations, food safety, roads and infrastructure, and value chain coordination; (2) flexibility in financial arrangements, insurance and planning to cope with, and be responsive to, variability in climate and markets; and (3) integration of the interdisciplinary research to form a more holistic and service-oriented approach based on science to inform policy. For research to be utilized most effectively in policies related to CSA, pathways for communication of the latest scientific progress and research results must be established within relevant time frames. Communication must span sectors and scales in which policymakers and other stakeholders operate, crossing boundaries between scientists and local, regional and global actors such as nongovernmental organizations, governmental agencies, corporations and broad social and media networks [290].

CSA strategies support the realization of a broader green economy concept that acknowledges 'the sum total of all ecosystem services and how they collectively provide the complete life support system we need' [292], p. 9. In practice, market prices, costs, and benefits for the ecosystem services related to carbon sequestration, clean water production, flood protection and grass forage have been quantified. In Cameroon, for instance, the value (in US\$·ha⁻¹·yr⁻¹) attributed to the forest's contribution to climate and flood control is 1.3- to 2.6-fold greater than that of the timber, fuel wood and nontimber products. Coordinated action resulting from CSA and green economy research not only realizes the improvement of livelihoods and food security through mitigation and adaptation to climate change but also creates cobenefits for ecosystem services and sustainable use of natural capital and enables evaluation of a broader set of trade-offs associated with a certain course of action.

Conclusions

Disciplinary, interdisciplinary and transdisciplinary scientific approaches play a fundamental and profound role in developing understanding of the processes underlying CSA and serve as partners in enumerating priorities for CSA. They form a crucial element in the knowledge base needed to implement CSA actions and manifest future transformative changes in agriculture in a changing climate. Global science conferences on CSA have already been influential in assembling scientists and other stakeholders to share knowledge [17,49]. A third conference in Montpellier, France, is planned for 2015 with the following agenda items: discussion key scenarios in agriculture and food systems, identifying priorities for early

action and designing a roadmap for moving forward with an action plan. These objectives set the stage for a much stronger emphasis on knowledge-to-action frameworks, capacity-building and the changes in human behaviour and social infrastructure that are necessary for adaptation and resilience [133,152,293]. The momentum that has already built among the science community for CSA forms the foundation for critical engagement by more researchers in fundamental and applied studies. To this end, establishing a more formal governance mechanism to embed science in the information base for the CSA Alliance, would be a vital step in developing priorities, scientific engagement and funding to support the knowledge needed for policymaking decisions.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

KLS, AKH and LEJ cowrote the manuscript. AJB, MRC, AC, CJC, JLH, KH, JWH, WRH, LSJ, BMJ, EK, RL, LL, MNL, SM, RP, MPR, SSS, WMS, MS, PT, SJV, SMW and EW contributed content. All authors read and approved the final manuscript.

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