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Beyond yields: Climate change effects on specialty crop quality and agroecological management

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Abstract

Climate change is impacting the sustainability of food systems through shifts in natural and human dimensions of agroecosystems that influence farmer livelihoods, consumer choices, and food security. This paper highlights the need for climate studies on specialty crops to focus not only on yields, but also on quality, as well as the ability of agroecological management to buffer climate effects on quality parameters. Crop quality refers to phytonutrient and secondary metabolite profiles and associated health and sensory properties that influence consumer buying decisions. Through two literature reviews, we provide examples of specialty crops that are vulnerable to climate effects on quality and examples of climate-resilient agroecological strategies. A range of specialty crops including fruits, vegetables, tree nuts, stimulants, and herbs were identified to respond to climate variables with changes in quality. The review on climate-resilient strategies to mitigate effects on crop quality highlighted a major gap in the literature. However, agricultural diversification emerged as a promising strategy for climate resilience more broadly and highlights the need for future research to assess the potential of diversified agroecosystems to buffer climate effects on crop quality. We integrate the concepts from our literature review within a socio-ecological systems framework that takes into account feedbacks between crop quality, consumer responses, and agroecosystem management. The presented framework is especially useful for two themes in agricultural development and marketing, nutrition-sensitive agriculture and *terroir*, for informing the design of climate-change resilient specialty crop systems focused on management of quality and other ecosystem services towards promoting environmental and human wellbeing.

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Introduction

Climate change is impacting the sustainability of food systems globally and is presenting challenges and opportunities for farmer livelihoods, markets, and food security (Wheeler and von Braun, 2013). Increased global temperatures and carbon dioxide levels over the past six decades, coupled with greater weather variability and more extreme weather conditions such as droughts and floods, are impacting crop yields and shifting the geographical ranges of crop cultivation (Ewert et al., 2005). Lobell et al. (2011) modeled weather data with historical yields of the four largest commodity crops over the past forty years and found that global maize and wheat production declined by 3.8% and 5.5% respectively, while increased temperatures in higher latitudes enhanced yields of some crops. At the same time, while agriculture is vulnerable to climate dynamics, it is also a major driver of global environmental change, contributing to more than 25% of global greenhouse gas emissions (Edenhofer et al., 2014).

There are multiple ways to examine climate effects on food systems, and these vary based on scientific discipline and approach. Studies in the biophysical sciences have focused on how and why climate variables impact crops and the ecological and agroecosystem management factors that increase or decrease resilience (Côté and Darling, 2010; Porter and Semenov, 2005; Easterling et al., 2000; Altieri et al., 2015). Research in the social sciences has focused on assessing producer responses to climate change, including perceptions and knowledge of climate change, impacts of climate change on farmer livelihoods and food security, traditional and local ecological knowledge, adaptation and mitigation strategies, and variables that promote cultural resilience to change (Nabhan, 2010; Thomas et al., 2007). A much smaller body of work in the socio-ecological literature links the biophysical components of agroecosystems with social components and assesses dynamic feedbacks (Ahmed et al., 2014a; Bergamini et al., 2013; Kellogg et al., 2010; McKey et al., 2010).

To date, studies from the biophysical sciences examining climate effects on agroecosystems have largely focused on crop yields (Porter and Semenov, 2005). Crop yields are crucial to understand because of their direct and indirect effects on food supply, crop prices, and farmer livelihoods (Hertel et al., 2010). In addition to yields, quality is also an important factor to understand for its' impact on consumer-buying decisions and human nutrition and health, but it is less frequently acknowledged. Crop quality as presented here refers to phytonutrient and secondary defense metabolite profiles (i.e. bioactive food components or phytochemicals) and associated health attributes and sensory properties as well as food safety. Quality parameters include the presence and concentrations of phytonutrients and secondary metabolites, bioactivity, as well as organoleptic properties such as color, visual appeal, aroma, taste, and texture (Mattos et al., 2014; Ahmed et al., 2015) as well as shelf life. Concentrations of toxins and presence of specific microorganisms may further be used to measure food safety aspects of food quality. Human consumers have the ability to perceive shifts in crop quality and these perceptions can influence their buying decisions and affect the demand, price, and other economic dimensions of agricultural products.

Assessing crop quality is particularly important for specialty crops where quality is determined in large part by the presence and concentrations of specific phytonutrients and secondary metabolites that benefit consumers (Ahmed et al., 2014a). Specialty crops are defined as fruits, vegetables, tree nuts, and horticulture and nursery crops that are managed and used by people for food, medicinal, or aesthetic purposes (USDA, 2015). Consumer perceptions of specialty crop quality is a key component characterizing human interactions with agroecosystems as it is related to an ecosystem service that human can directly distinguish through their senses. Previous research has highlighted how humans have an ability to discern sensory properties of agricultural products from different environmental and management conditions (Ahmed et al., 2010). For example, consumers were able to discern tea harvested from shade-grown agro-forests versus sun-grown terrace gardens on the basis of flavor (Ahmed et al., 2010). Tea from shade-grown agro-forests was also considered to be of higher quality compared to those from terrace gardens on the basis of the key antioxidant secondary metabolites linked to tea's health-related and flavor properties (Ahmed et al., 2013). In addition, the sensory and secondary metabolite profiles of tea products has been found to vary with shifting climate variables including changes in precipitation that influence consumer purchasing decisions and farmer livelihoods (Ahmed et al., 2015).

The goal of this paper is to highlight the need for climate studies on specialty crops to focus not only on yields, but also on quality within a socio-ecological systems framework (Ostrom, 2009; Mertz et al., 2009; Walker et al., 2006; Cumming et al., 2005; Folke et al., 2004; Abel and Stepp, 2003; Stepp et al., 2003) that links biophysical components of agroecosystems with social components and assesses dynamic feedbacks between the two (Ahmed et al., 2014a; Bergamini et al., 2013; Kellogg et al., 2010; McKey et al., 2010). First, we present background on climate effects on specialty crop quality and agroecosystem management to situate our review in the areas of chemical ecology, secondary metabolite chemistry, agroecology, and socio-ecological systems. Next, we present findings from two literature reviews including a review on climate effects on specialty crop quality and a review on agroecosystem management strategies that have the potential to buffer climate impacts on crop quality and other parameters. Ultimately, we integrate and summarize the concepts from our background and literature reviews in a socio-ecological systems framework that takes into account feedbacks between crop quality, consumer responses, and producer management of agroecosystems. The framework presented here can be applied by interdisciplinary research teams and natural resource managers to collect evidence to inform the design of climate-change resilient food systems focused on the management of crop quality and other ecosystem services towards promoting environmental and human wellbeing. For example, our integrative framework has tremendous applicability in the emerging area of nutrition-sensitive agriculture for addressing food security issues of inadequate dietary quality.

Background

Climate effects on specialty crop quality

Examining environmental and management effects on crop quality draws on plant-defense theories of chemical ecology as well as the related area of secondary metabolite chemistry. According to plant-defense theories, plants are continuously exposed to a plethora of abiotic and biotic stresses in their environment such as pathogens, herbivores, and ultraviolet radiation. As sessile organisms, plants can not protect themselves from these stress factors through movement and have evolved secondary metabolites as defense compounds to protect themselves from various abiotic and biotic stresses (Fraenkel, 1959; Feeny, 1976; Coley et al., 1985;

Harborne, 1993) such as mediating interactions with pathogens and other organisms (Piasecka et al., 2015). Some secondary metabolites also serve as signal compounds to attract pollinating and seed-dispersing animals (Wink, 2015). Unlike primary metabolites (e.g. carbohydrates, lipids, proteins) that are ubiquitous across the plant kingdom for their crucial role in plant growth, development, reproduction and other basic photosynthetic and respiratory metabolic processes, secondary metabolites support the long-term survivability of plants, and their absence or low levels may not result in immediate plant death. Numerous studies have demonstrated that secondary metabolites are usually not present in fixed levels but instead transform and cycle through plant parts based on the activation of various secondary metabolite pathways in response to a number of environmental and temporal factors (Harborne, 1993; Bednarek, 2012). The synthesis of secondary metabolites represents a metabolic cost for plants through the allocation of energy diverted away from growth and development. Thus, plants tend to produce these compounds in notable concentrations only if they have the ecological cue to do so based on interactions between their genetics, physiology, and prior history and environmental stressors (Coley et al., 1985; Glynn et al., 2007). There are over 100,000 known secondary metabolites with diverse chemical structures and function (Swift et al., 2004). Major classes of secondary metabolites include phenolics (~8,000 known compounds), alkaloids (~12,000 known compounds), terpenoids (~25,000 known compounds), and sulfur containing compounds (Goldberg, 2003).

Previous research has demonstrated how secondary metabolite profiles of crops vary significantly on the basis of genetic (van Dam & Vrieling, 1994), environmental (Björkman et al., 2011; Ahmed et al., 2014a, 2014b) and management (Baranski et al., 2014; Ahmed et al., 2013) conditions. Changes in precipitation, temperature, carbon dioxide levels, soil composition, herbivory, and agroecological practices have all been shown to influence the presence and concentrations of secondary metabolites in plants (Glynn et al., 2007; Tharayil et al., 2011; Baranski et al., 2014; Myers et al., 2014). For example, Myer et al. (2014) demonstrated that increasing carbon dioxide concentrations resulted in decreased concentrations of zinc and iron in C_3 grains and legumes with implications for human nutrition. Climate variables may also influence antioxidant activity of specialty crops (Mattos et al., 2014). For example, temperature is recognized as the most significant factor affecting antioxidant activity in vegetables and fruits (Mattos et al., 2014) and increased temperatures have been shown to generally reduce vitamin content in fruit and vegetable crops (McKeown et al., 2006). Agroecological management further influences secondary metabolites; a recent systematic review and meta-analysis of 343 peer-reviewed publications showed that organically produced crops and food items have statistically higher concentrations of antioxidant secondary metabolites compared to those produced in conventional systems (Baranski et al., 2014).

Shifts in crop secondary metabolite profiles in response to biotic and abiotic factors create dynamic feedback loops in agroecosystems through a cascade of effects impacting multi-trophic interactions such as changes in herbivore pressures and plant-pollinator dynamics (Harvey and Malcicka, 2015). Secondary metabolites and other quality parameters of specialty crops may further be impacted post-harvest from handling, processing, distribution, storage and preparation. In addition to changes in secondary metabolites, crop quality may further be impacted through changes in physical sensory properties such as texture. For example, high temperature conditions during fruit growth have been found to impact fruit firmness (Mattos et al., 2014).

Plant secondary metabolism provides ecosystem services through its' role in regulating biological populations including diseases and pests as well as for imparting plant products their nutritional and health attributes for human consumers (Swift et al., 2004). Secondary metabolites offer a library of bioactive compounds that may have deleterious, neutral, or beneficial properties for human consumers. Many secondary metabolites are recognized to have a beneficial role for human wellbeing at specific concentrations including the potential to mitigate micronutrient deficiencies and associated risks of chronic disease (Johns and Sthapit, 2004; Myers et al., 2014; Poiroux-Gonord et al., 2010; Swift et al., 2004). Several secondary metabolites are essential for human life including vitamins such as vitamin E (Poiroux-Gonord et al., 2010) while others have been show to treat or prevent health conditions through their anti-inflammatory, antimicrobial, antioxidant and stimulant properties (Swift et al., 2004).

Human consumers can perceive shifts in secondary metabolite profiles through their senses. Changes in secondary metabolites can enhance or negatively influence flavor and other sensory experiences of foods and indicate changes in the health properties and other physiological attributes of foods. For examples, consumers may observe changes in secondary metabolites through variations in color or flavor. Previously, increased temperatures were shown to result in berries that are redder and darker (Galletta and Bringhurst, 1990); these color changes may indicate that certain secondary metabolites such as anthocyanins are being produced in greater concentrations. Some changes in secondary metabolites due to biotic and abiotic stress may alter the mechanism of action of these compounds and their implications for human health. For example, temperature can affect particular chemical reactions, resulting in some compounds shifting from antioxidant to pro-oxidants (Marinova and Yanishlieva, 2003; Mattos et al., 2014). Ultimately, these consumer perceptions may impact food choices, preferences, and eating habits.

Producer income is impacted by consumer perceptions of crop quality and associated demand and price point for agricultural products. For example, producer income can benefit from consumer preference for high-quality crops as determined by the sensory ability to perceive quality through parameters such as flavor and color and expressed through price premiums and demand. Human preferences and ability to discern markers of quality may vary over time and between individuals and cultures. However, a consensus for what constitutes markers of quality emerges for many crops and this is reflected in market prices and demand for crops grown in particular habitats, microclimates, and management systems.

Agroecosystem management for climate mitigation

Just as plant-environment interactions create dynamic feedbacks loops in agroecosystems where crops are both impacted by biotic and abiotic factors, human-environment interactions with agroecosystems and broader socio-ecological systems create dynamic feedback loops in which humans impact and are impacted by the biophysical environment (Levin, 1999). For example, not only are climate patterns changing, human societies are also changing through adaptation strategies such as crop and livelihood diversification (Mertz et al., 2009) that can serve to mitigate risk in agroecosystems and food systems more broadly. It is thus important to evaluate human dimensions of agroecosystems and broader socio-ecological systems to mitigate climate risk in food system. This is particularly important given the recognition that there is as much diversity in the human dimension of management as in the biophysical resources managed by farmers (Nowak and Cabot, 2004).

An agroecological approach has been promoted as a way to adapt to and mitigate climate change by developing and implementing alternative ways in agricultural production that mimic or augment natural processes by incorporating interactions among plants, animals, insects, people, and natural resources (Altieri et al., 2015; Jiggins, 2014). Common agroecology management principles include recycling nutrients and energy on a farm, diversifying species and genetic resources spatially and temporally, and focusing on interactions and productivity across the agricultural system rather than on individual species (De Schutter, 2012). The theory underlying our focus on the role agroecosystem management for climate mitigation draws from the socio-ecological systems literature and infers that the adaptive capacity and resilience of agroecosystems to exogenous change are a function of both the biophysical ecology as well as the decision-making and other social dimensions of resource managers (i.e. human ecology and agency; Walker et al., 2006; Folke, 2006). Adaptive capacity refers to the ability of ecological and social systems to adapt to environmental changes (Gunderson and Holling, 2009). Resilience refers to the capacity of a system to absorb disturbance and re-organize while undergoing change so as to maintain the same function, structure, identity and feedbacks (Walker et al., 2004). Focusing on the resilience of a socio-ecological system such as an agroecosystem emphasizes interactions of non-linear dynamics, thresholds, uncertainty during the interplay of periods of gradual and rapid change across temporal and spatial scales (Folke, 2006). A loss of adaptive capacity and resilience within ecological and social domains of an agroecosystem indicates a vulnerable socio-ecological system (Folke, 2006).

Decision-making of managers of agroecosystems and other natural resource systems is based on interactions between individual and shared cognitive dimensions and cultural contexts that include perceptions, beliefs, knowledge, and experiences (Atran et al., 1999; Craik, 1943; Johnson-Laird, 1983). The variables influencing stakeholder decision-making can be evaluated towards better understanding human interactions with the world around them. Evaluating similarities and differences in collective decision-making across scales and between various stakeholders in the system allows for improved communication between stakeholders (Abel et al., 1998) as well as improved processes. In addition, it is well recognized that environmental problems are largely driven by human decisions and actions, as are solutions to address such problems (Jones et al., 2011).

Literature review methods

Climate effects on specialty crop quality

We carried out a literature review to provide examples of the influence of climate variables on specialty crop quality as determined by secondary metabolite profiles. A literature review was carried out in the following databases: PubMed, Scopus, and Science Direct. We used a derivation of the following search terms: "Climate change" AND (quality OR nutrient* OR phytochemical* OR secondary metabolite* OR antioxidant* OR phenolic*) AND (crop OR fruit OR vegetable OR seed OR nuts). Derivations of these search terms replaced "Climate change" with another climate variable including "global change", "climate variability", "weather", "seasonality", "temperature", "precipitation", "rainfall", and "carbon dioxide." The search was restricted to scientific articles from 2000 to 2014. Literature was screened for relevance using the following inclusion criteria: (i) any geographical location; (ii) any size and type of production system and, (iii) English papers only.

Agroecosystem management for climate mitigation

We also carried out a literature review to provide examples of agroecosystem management strategies to mitigate climate impacts on crop quality. Using a similar methodology as above, a review was carried out in Science Direct, Web of Knowledge, and Agricola using the search terms (climate change OR global change) AND (agro-ecosystem* OR crop system*) AND (quality OR nutrient* OR phytochemical* OR secondary metabolite*) AND (adaptation OR mitigation). The search was restricted to scientific articles from 2000 to 2014. However, as this search found a scarcity of relevant articles, we carried out an additional search to provide examples of management strategies that can be used to design climate-change resilient food systems. This additional review was also carried out in Science Direct, Web of Knowledge, and Agricola for the period 2000 to 2015 and used the search terms (climate change OR global change) AND (agro-ecosystem* OR crop system*) AND (adaptation OR mitigation).

Literature review findings

Climate effects on specialty crop quality

Findings from the search generated over 1,500 articles of which 86 articles matched the purpose of our search. Table 1 highlights examples of 20 specialty crops identified from our literature search that are vulnerable to climate effects on quality as determined by secondary metabolite profiles. This includes a range of specialty crops including fruits (apple, bilberries, fig, pomegranate, plantain, and strawberries), vegetables (kale and tomatoes), stimulants and other beverage crops (tea, coffee, mate, hops for beer production, and grapes for wine production), tree nuts (peanuts), and herbs (coriander, oregano, and peppermint). Table 1 further highlights how various climate variables including temperature, precipitation, humidity, solar radiation, and carbon dioxide levels may impact crop quality and measured by changes in secondary metabolite concentrations that influence sensory properties and health-related benefits for human consumers. Quality parameters may increase or decrease in response to various climate shifts. For example, while seasonal temperature was inversely correlated with anthocyanin accumulation in pomegranates (Borochov-Neori et al., 2011), day and night

Table 1. Climate effects on specialty crop quality [a]

Specialty crop	Climate variables	Secondary metabolites	Findings	Quality implications	Author(s)
Apple (*Malus domestica*)	Temperature, humidity, and rainfall	Volatiles (terpenoids)	Rainfall, temperature, and humidity influence terpenes and volatiles	Flavor	Vallat et al. (2005)
Bilberries (*Vaccinium myrtillus*)	Overall climate and thermal sum	Anthocyanidin (phenolics)	Anthocyanidin concentration in bilberries are influenced by climatic factors	Sensory quality; health-related benefits	Akerström et al. (2009)
Brown rice (*Oryza sativa*)	Temperature	Tocotrienols and tocopherols (phenols)	Alpha-tocotrienol and/or alpha-tocopherol increased at elevated temperature whereas gamma-tocopherol and gamma-tocotrienol decreased	Health-related benefits	Britz et al. (2007)
Coffee (*Coffea arabica*)	Temperature	Chlorogenic acids (phenols), fatty acids	Environmental temperature during development dramatically influenced fatty acid content	Health-related properties	Villarreal et al. (2009)
Coriander (*Coriandrum sativum*)	Overall climate	Linalool and camphor essential oils (terpenes)	Weather conditions in 1997-favored linalool and camphor concentrations in coriander fruits	Sensory qualities	Gil et al. (2002)
Fig (*Ficus carica*)	Overall climate	Flavor compounds (terpenes)	All 8 individual compounds analyzed showed statistically significant differences due to the influence of climatic conditions	Sensory qualities	Darjazi and Larijani (2012)
Grapes (*Vitis* sp.)	Temperature, solar radiation, rainfall	Phenolics and antioxidant properties	Cooler temperatures were positively correlated to phenolic compounds and antioxidant properties	Sensory quality; health-related benefits	Xu et al. (2011)
	Carbon dioxide levels	Tartaric acid	Tartaric acid increased with a rise in carbon dioxide level	Sensory quality	Bindi et al. (2001)
Hops (*Humulus lupulus*)	Overall climate	Alpha-acids, beta-acids, desmethylxantho-umol, xanthohumol	Concentrations of key compounds depended on climatological conditions with highest levels in poorest weather conditions	Sensory qualities; health-related benefits	Keukeleire et al. (2007)

Specialty crop	Climate variables	Secondary metabolites	Findings	Quality implications	Author(s)
Kale (*Brassica oleracea* var. *sabellica*)	Mean temperature and mean global radiation level	Antioxidant activity and total phenolic content	Antioxidant activity and total phenolic content were influenced by genotype and climatic factors	Health-related benefits	Zietz et al. (2010)
Mate (*Iles paraguariensis*)	Rainfall and temperature	Phenolic concentration and antioxidant capacity	Lower rainfall, temperature, and drying had varying effects on phenolics	Sensory qualities; health-related benefits	Heck et al. (2008)
Oregano (*Origanum* spp.)	Temperature	Phenolic concentration, antioxidant activity, essential oil composition (terpenoids)	Temperature explains a majority of the variation of secondary metabolite luctuations in oregano	Sensory qualities; health-related benefits	Dambolena et al. (2010)
Peanut (*Arachis hypogaea*)	Temperature and rainfall	Ratio of oleic to linoleic acids (fatty acids) and the tocopherol content (phenols)	Mean temperature and total precipitation were found as explanatory variables for variations in oleic to linoleic acid ratios. Total precipitation impacts tocopherol content	Sensory qualities; health-related benefits	Casini et al. (2003)
Peppermint (*Mentha* x *piperita*)	Solar radiation	Monoterpenoid essential oil	High levels of natural sunlight is positively correlated with monoterpenoid concentrations	Sensory quality; health-related properties	Behn et al. (2010)
Plantain (*Plantago lanceolata*)	Seasonal variation	Catalpol, aucubin, and acteoside (glucoside)	Aucubin and acteoside concentrations increased from spring to mid-fall and acteoside declined steadily during the summer	Health-related benefits	Tamura and Nishibe (2002)
Pomegranate (*Punica granatum*)	Temperature	Anthocyanins (phenolics)	Seasonal temperature was inversely correlated to anthocyanin accumulation	Sensory quality; health-related benefits	Borochov-Neori et al. (2011)
Shea tree (*Vitarella paradoxa*)	Temperature	Tocopherols (alpha, beta, gamma, delta; phenols)	Hot dry climates were positively correlated with alpha-tocopherol levels	Seed fat content	Maranz and Wiesman (2004)
Sugar maple (*Acer saccharum*)	Temperature	Total phenolic concentrations	Increased temperatures are related to an upregulation of total phenolic concentration	Sensory quality; health-related benefits	Ahmed et al. (in prep.)
Strawberry (*Fragaria* x *ananassa*)	Temperature	Phenolics (flavonoids) and antioxidant activity	Warmer nights and days had higher antioxidant activity and flavonoids than cooler days	Sensory quality; health-related benefits	Wang and Zheng (2001)
Tea (*Camellia sinensis*)	Precipitation	a. Catechins (phenolics), methylxanthines and antioxidant activity b. Volatiles	a. Drought upregulates total catechins and methylxanthines concentrations; b. Drought associated with greater concentrations of volatile compounds	Sensory quality; health-related benefits	a. Ahmed et al. (2014a); b. Kowalsick et al. (2014)
Tomato (*Solanum lycopersicum*)	Influence of Mediterranean and continental water	Lycopene, carotene, lutein, tocopherols	Mediterranean weather conditions have contributed to increased concentration of total carotenoids and lycopene	Sensory quality; health-related benefits	Kacjan-Maršič et al. (2010)

[a]Examples of climate effects on specialty crop quality identified in the literature. This includes a diverse range of specialty crops including fruits, vegetables, beverage crops, nuts, and seasonings as well as a range of climate variables (temperature, precipitation, humidity, solar radiation, and carbon dioxide levels) and groups of secondary metabolite classes (phenolics, terpenoids, alkaloids, and fatty acids) that are related to various health-related attributes for human consumers.

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temperatures were positively correlated with antioxidant activities in strawberries (Wang and Zheng, 2001). In addition, climate variables were found to impact diverse groups of secondary metabolite classes including phenolics, terpenoids, alkaloids, and fatty acids that are related to a range of health-related attributes for human consumers such as nutrition, antioxidant, and anti-inflammatory properties (Wink, 2015).

Agroecosystem management for climate mitigation

The literature review on agroecosystem management strategies to mitigate climate impacts on crop quality did not result in adequate relevant results. These findings highlight the notable gap in the literature in this area and the urgent need of future studies to integrate crop quality when evaluating the ability of various agroecosystem management strategies to buffer climate risk. Given the scarcity of literature on agroecosystem management strategies to mitigate climate impacts on crop quality, we carried out an additional literature review to provide examples of management strategies to mitigate climate risk in agroecosystems.

Following is a summary of climate-change resilient farming strategies identified in the literature: (i) agricultural diversification (Altieri et al., 2015; Schwendenmann et al., 2010; Lin, 2011; Howden et al., 2007; Fraser, 2007; Di Falco and Perrings, 2003), (ii) tree planting (Bhattarai et al., 2015; Kotecký, 2015), (iii) varietal and/or crop substitution (Kurukulasuriya and Mendelsohn, 2008; Moniruzzaman, 2015; Bradshaw et al., 2004; Seo and Mendelsohn, 2008; Malanson et al., 2014), (iv) changing harvest and/or labor calendars (Waha et al., 2013; Olesen et al., 2011), (v) management of soil organic matter and carbon sequestration through no-tillage (Fuhrer and Chervet, 2015; Lal, 2004), mixed crop-livestock systems (Thornton and Herrero, 2014), and organic agriculture (Lotter, 2003), (vi) controlling pests and disease such as through 'climate-adapted-pull-push strategies' (Midega et al., 2015), (vii) water management through improvement of water allocation or irrigation efficiency (Chartzoulakisa and Bertaki, 2015), precision agricultural management (Lal et al., 2011), rainwater harvesting (Pandey et al., 2003), cover cropping with nurse plants or other plants (Delgado et al., 2007), and conservation (Delgado et al., 2011), (viii) environmental modification with technology and/or other management practices (Lybbert and Sumner, 2012), (ix) use of biotechnology (Tester and Langridge, 2010; Varshney et al., 2011), (x) changing farming practices on the basis of utilization efficiency (Guo et al., 2015), (xi) changes in post-harvest processes such as new processing technologies, repurposing the end-use of the product, creating new marketing schemes, and promoting new attributes of the product (Mattos et al., 2014; Stathers et al., 2013; Beddington et al., 2012), (xii) migration and relocating the agroecosystem to a more suitable location (Bardsley and Hugo, 2010; Farauta et al., 2012) and, (xiii) adaptive governance (Cooper and Wheeler, 2015).

Based on the authors' ongoing work on examining the role of diversified agro-forests to buffer climate effects on crop quality, we support that further studies should examine the capacity of diversified agriculture to mitigate climate impacts on crop quality. Surveys with tea farmers in southern Yunnan of China indicate that tea agro-forests, diversified cropping systems, tea grown from seed, and tea gardens that are surrounded with diverse forest buffers are more resilient to climate variability compared to monoculture terrace tea gardens while also having higher quality (Figure 1; Ahmed et al., 2014a). Here, we summarize the importance of diversified agriculture (Schwendenmann et al., 2010; Vandermeer et al., 1998; Lin, 2011; Yachi and Loreau, 1999; Altieri, 1999) for climate-change resilient agroecosystems more broadly including as a potential strategy to mitigate climate effects on quality. We further focus on agricultural diversification of the strategies identified in the literature because it is relatively affordable for smallholder farmers given that it relies on ecosystem services rather than expensive external inputs (Lin, 2011). In addition, agricultural diversification at the field and landscape level has been identified as a key adaptation strategies for responding to climate change in ways that will modify the dominant monoculture mode of food production (Altieri et al., 2015). Agricultural diversification includes practices such as agroforestry, crop rotations, mixed cropping, landscape mosaics, polycultures, and maintenance of diverse landraces.

Numerous previous studies have highlighted that agricultural diversification strategies are crucial for resilience (Tscharntke et al., 2011; Jacobi et al., 2015; Lin, 2011; Vandermeer et al., 1998; Yachi and Loreau, 1999). Different species or genotypes within an agroecosystem may perform different functions (Vandermeer et al., 1998) and have different physiological thresholds in response to climate variability (Yachi and Loreau, 1999) and thus enhance the resilience of an ecosystem (Walker, 1995) or agroecosystem. Agroecosystems with greater plant species diversity offer more host plant species for pests as well as natural pest predators and thus help suppress pest outbreaks (Altieri, 1999). Tree-based cropping systems such as agro-forestry provide several mechanisms that can mitigate the impacts from extreme weather events (Schwendenmann et al., 2010). More structurally complex systems can buffer crops from large fluctuations in temperature and extreme storm events and maintain conditions that are more optimal for specific crops (Lin, 2007, 2011). Thus, even if climate conditions have the potential to reach or exceed thresholds for crops, managing the microclimate of agroecosystems by maintaining forest canopy can mitigate climate risk. At the same time, improvements in agricultural systems through diversification strategies offer the potential to mitigate climate risk by increasing carbon stocks and reducing emissions (Jose, 2009; Sharrow and Ismail, 2004; Kirby and Potvin, 2007).

(a)

(b)

Figure 1

Diversification of agriculture for climate resilience.

Diversification of agriculture is a key strategy for climate-change resilient food systems and includes practices and strategies such as agro-forestry, crop rotations, mixed cropping, landscape mosaics, polycultures, and maintenance of diverse landraces. For example, surveys with tea farmers in southern Yunnan of China indicate that tea agro-forests (a) are more resilient to climate variability compared to monoculture terrace tea gardens (b).

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Socio-ecological framework to examine feedbacks between climate effects on crop quality and agroecological management for mitigating climate risk

Here, we integrate the two concepts highlighted in our background and literature review above on climate effects on specialty crop quality and agroecological management for mitigating climate risk into a socio-ecological systems framework that can be applied for future studies towards designing climate-change resilient specialty crop systems focused on the management of quality and other ecosystem services. This integrative socio-ecological systems framework is composed of two conceptual models. The first model illustrates the most vulnerable types of crops with respect to quality. The second model focuses on agroecosystem management responses for climate mitigation. These conceptual models are based on principles and conventions set forth in Stepp (1999) and Pavao-Zuckerman (2000) that allow for describing the relationships between model components without formal quantitative equations. The integration of these models into a socio-ecological systems framework allows for the evaluation of feedbacks between crop quality, consumer responses, and agroecosystem management. Constructing and applying integrative frameworks for understanding human interactions with the environment has been identified as a priority in developing policies for sustainability (Liu et al., 2007). In addition, the application of an integrative socio-ecological framework by different research teams allows for systematic comparison of findings obtained in a wide variety of contexts towards increasing our capacity to more effectively develop strategies for sustainability (Ostrom, 2009).

Conceptual model 1: Vulnerability of crop quality

We developed a conceptual crop quality model (Figure 2) to describe the types of crops that are most vulnerable to climate effects on quality. In our conceptual crop model, crops are classified into two main categories: those crops whose quality profile and market value is mainly determined by primary metabolites (Crop Type 1) and those crops whose quality profile and market value is mainly determined by secondary metabolites (Crop Type 2). We further sub-classify crops on the basis of their environmental plasticity and physiological thresholds. The genome of some crops and crop varieties such as potatoes and maize has physiological thresholds to adapt to a wide range of environmental conditions (Crop Type 1a and Crop Type 2a). Others crops are more restricted with a genetic makeup of narrower thresholds that limit the range of environmental conditions in which these crops can survive and are thus more vulnerable to changes such as global environmental change (Crop Type 1b and Crop Type 2b). In particular, crops whose quality is determined by secondary metabolites *and* that have restricted environmental range are expected to be the most vulnerable to climate variability (Crop Type 2b). The need to assess climate effects on quality is particularly relevant for this vulnerable crop type whose quality mainly derives from secondary metabolite composition, such as phytonutrient-dense fruits and vegetables and beverage items such as tea, coffee, hops, and wine. For such specialty crops, changes in crop quality are as important for farmer livelihoods and food security if not more than changes in crop yield (Ahmed et al., 2013).

Conceptual model 2: Agroecosystem management for climate mitigation

We summarized strategies identified in our literature review on agroecosystem management to mitigate climate risk in a conceptual model on producer responses to climate change (Figure 3). This conceptual model emphasizes the inherent nature of humans to constantly experiment and innovate in agroecosystems, even when environmental conditions are relatively stable (Stepp et al., 2003). In addition, this conceptual model emphasizes that farmers and other natural resource managers have variable responses to climate and other

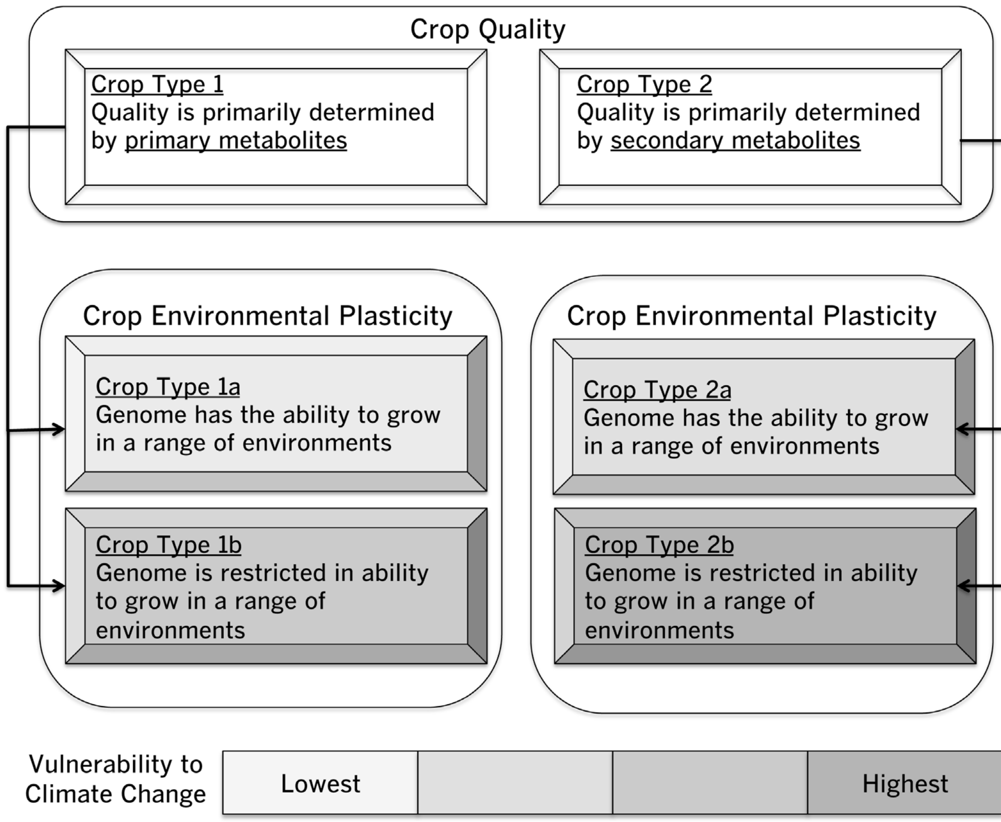

Figure 2

Crop classification model on the basis of quality determination.

Crops can be classified on the basis of their quality including those whose quality profile is mainly determined by primary metabolites (Crop Type 1) and those whose quality profile is mainly determined by secondary metabolites (Crop Type 2), such as specialty crops including fruits and vegetables, tea, coffee, grapes, and chocolate. In this crop classification model, we further sub-classify crops here on the basis of their environmental plasticity including those that are able to adapt to a wide range of environmental conditions (Crop Type 1a and Crop Type 2a) and those that are restricted to a range of environmental conditions (Crop Type 1b and Crop Type 2b).

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exogenous change that depend on a range of cognitive, cultural, and experiential dimensions (Stepp, 1999). Producers may or may not respond to climate shifts in their agroecosystems depending on the following human dimensions: (i) expertise and knowledge adapted to spatial and temporal heterogeneity, (ii) cultural norms, social networks and collective management, (iii) perceptions of climatic variation and impacts of this variation on crops, (iv) access to resources such as land tenure and finances and, (v) cultural memory that encompasses knowledge, beliefs, and values (Gbetibouo, 2009; Abel and Stepp, 2003). Farmers make management decisions on the basis of these cognitive, cultural, and personal dimensions; in turn, these decisions mediate the effects of climate variables on processes in agroecosystems. The more resilient the social dimensions of food systems, the more likely that natural resource managers will develop and implement effective strategies for climate-change resilient food systems. Alternatively, farmers may not respond or respond inadequately to climate effects in their agroecosystem due to political, socio-economic, geographical, and cultural factors as well as barriers related to infrastructure, knowledge, skills, and resources. Epistemological filters may have a particular effect on preventing change (Stepp, 1999). For example, farmers that do not perceive climate effects and/or do not have knowledge of climate mitigation are more likely not to take any action to mitigate climate risks in their agroecosystems compared to those that perceive the effects of climate and/or have knowledge of mitigation strategies. There is thus a need to build smallholder capacity to best respond to and mitigate climate risk in agroecosystems that addresses political, socio-economic, geographical, and cultural factors as well as previous experiences that influence responses to global environmental change.

Integrative socio-ecological systems framework

The integrative socio-ecological framework presented here to assess climate effects on crop quality and agroecological management (Figure 4) highlights the feedbacks between the conceptual models presented above. At the core of this socio-ecological framework are agroecosystems (Figure 4a) and their natural (or biophysical) components (Figure 4b) and their human components (Figure 4c) as well as dynamic feedbacks between these dimensions (Figure 4d and 4e). The natural components of agroecosystems constitute of interactions between biotic and abiotic factors and associated processes (Figure 4b). Biotic factors of agroecosystems include all living organisms such as cultivated plants, livestock, soil microorganisms, pollinators, and herbivores while abiotic factors include physical and chemical components of the environment such as land, water, temperature, moisture, light, and nonliving components of soil. The human components in this framework include consumption and production stakeholders as well as associated processes such as interactions between these stakeholders (Figure 4c).

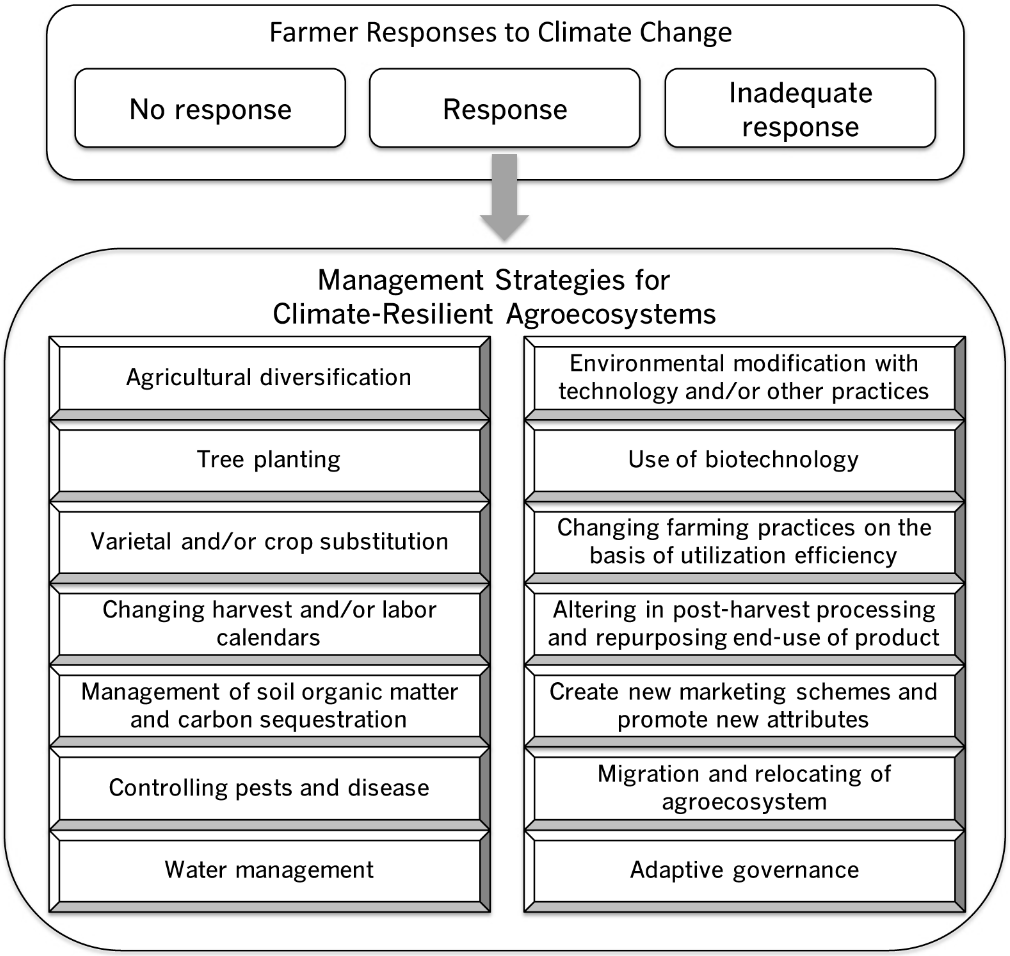

Figure 3

Farmer responses to climate change towards climate-change resilient agroecosystems.

Farmers may respond to climate change in variable ways in their agroecosystems including no response, inadequate response, or they may respond through various mitigation and adaptation strategies towards climate-change resilient agroecosystems.

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Two critical processes that link the natural and human components of agroecosystems are crop quality (Figure 4d) and climate adaptation and mitigation strategies (Figure 4e). Environmental and management factors within agroecosystems result in crops that vary in yield and quality. Producers and consumers (Figure 4c) may perceive changes in crop yields via market signals including shifts in availability and prices. Changes in crop quality (Figure 4d) may be perceived by sensory profiles and physiological properties that may be more or less desirable for consumers depending on their preferences. Consumers may respond to changes in crop quality on the basis of sensory perceptions and other market variables through purchasing behavior that influences market equilibria, demand, prices, and ultimately income derived for farmer livelihoods. Consequently, farmers and other natural resource managers may alter the way they manage their agroecosystems (Figure 4e) in response to consumer decision-making and markets in addition to direct observations in their agroecosystems. Furthermore, farmer responses may be dependent on knowledge acquired through social networks such as agricultural extension and community groups. Farmer responses influence agroecosystems through a range of adaptation, mitigation, and other management strategies (Figure 4e). Some of these agroecosystem management techniques may not only help mitigate climate risk, they may also serve to improve crop quality (Poiroux-Gonord et al., 2010).

The large arrows linking the agroecosystem (Figure 4a) to exogenous change (Figure 4f) highlights that agroecosystems are human-managed ecosystems that impact, and are impacted by, exogenous variables. Climate change, policies and markets are key exogenous factors that influences agroecosystems and alter outcomes for farmers, consumers, and the environment. While agroecosystems are vulnerable to the influence of exogenous factors, they also influence these factors. For example, agroecosystems influence climate change as major global drivers of greenhouse gas emissions (Edenhofer et al., 2014).

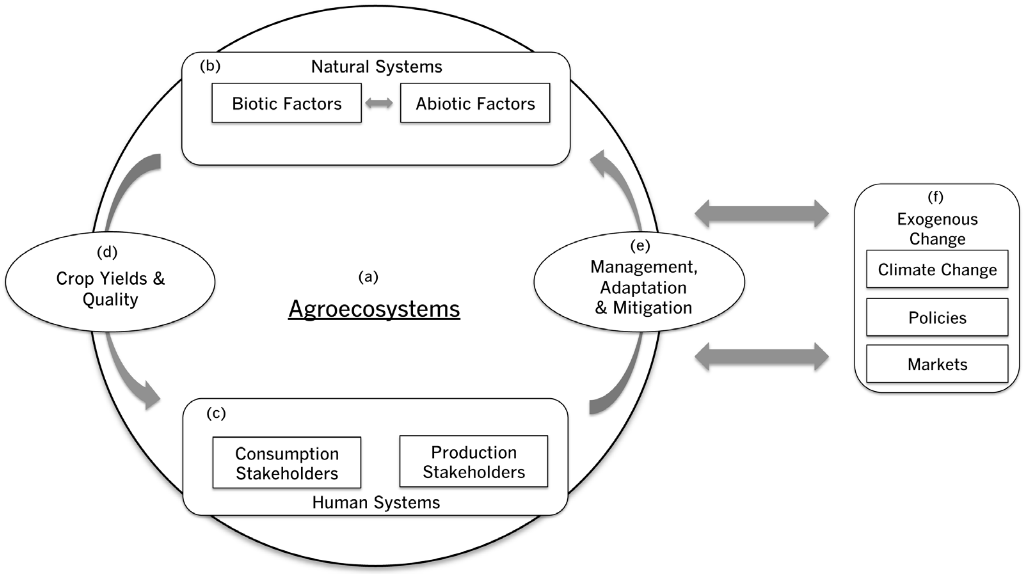

Figure 4

Socio-ecological systems framework to examine climate effects of crop quality and farmer responses.

This socio-ecological systems framework integrates two under-utilized concepts on specialty crop quality and agroecological management that can be applied for future studies on climate effects on specialty crop systems. Agroecosystems (Figure 4a) are the foundation of this framework with natural (or biophysical) components (Figure 4b) that produce crops and human components that interact with these crops (Figure 4c) through dynamic feedbacks (Figure 4d and 4e). Consumers (Figure 4c) may perceive changes in crop yields and quality (Figure 4d) via market signals and sensory profiles that may be more or less desirable for consumers depending on their preferences. Farmers and other natural resource managers may alter the way they manage their agroecosystems in response to consumer decision-making and markets as well as on the basis of their own direct observations, knowledge, and social networks through a range of management, adaptation, and mitigation strategies (Figure 4e). The large arrows linking the agroecosystem (Figure 4a) to exogenous change (Figure 4f) highlights that agroecosystems are human-managed ecosystems that impact, and are impacted by, exogenous variables.

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Application of framework to nutrition-sensitive agriculture and terroir

The framework presented above can be especially useful for two emerging themes in agricultural development and agricultural marketing including nutrition-sensitive agriculture and *terroir*. Nutrition-sensitive agriculture is an approach that is increasingly being used in development that seeks to maximize the contribution of agriculture to nutrition and household food security through such practices as increasing diversification of fruit trees and vegetables on smallholder farms and management techniques to foster nutrient-rich soils. Managing climate-resilient agroecosystems for high-quality crops directly addresses the food security goals of nutrition-sensitive agriculture (or agriculture-nutrition interventions) through supporting high-quality diets with food that have adequate nutrients. Crops with reduced quality may fail to provide adequate phytonutrients for human consumers and serve their role in mitigating micro-nutrient deficiencies (Baranski et al., 2014).

Our framework is further relevant to the agricultural commercialization and marketing theme of *terroir*. The concept of *terroir*, deriving from terre or land in French, is increasingly being used as a marketing strategy to discern and promote agricultural products on the basis of production characteristics including agroecological management and geography. *Terroir* is linked to a complex set of interactions between people, plants, and the ecosystem that give agricultural products a unique quality, typicality, or specificity of place. It encompasses all of the abiotic and biotic characteristics of a specific geography that interact with plant genetics and cultural practices that serve to differentiate one place from another in terms of agricultural production and the final quality of agricultural products. The concept of *terroir* emphasizes that deviations in crop quality occurs because of biophysical and human aspects characterizing different regions, farms, and even sections within the same farm. Managing agroecosystems and agricultural products for *terroir* involves focusing on the complex interactions of environmental and cultural factors that impart distinct characteristics to crops. A key aspect of cultivating crops for *terroir* is the focus on high quality. Another aspect of focusing on *terroir* is that factors that are beneficial for the environment are oftentimes also beneficial for human wellbeing (Ahmed et al., 2015). Our integrative framework can thus be used by research and production teams in managing for changes in *terroir* within the context of global environmental change.

Conclusion

Global environmental change and food security are among two of the most pressing societal issues today. Enhancing agroecosystem management to mitigate climate risk and building smallholder capacity are key strategies to address these issues (Parry et al., 2007). Scientific approaches are called for to inform the design of evidence-based solutions to address pressing climate change and food security issues. There are multiple ways to examine climate effects on food systems. This paper highlights the need for climate studies on specialty crops to focus not only on yields, but also on quality along with other ecosystem services, as well as the ability of agroecological management to buffer effects on quality parameters.

Our literature review on climate effects on specialty crop quality found that a range of studies have been carried out in this area and highlight that an array of specialty crops are vulnerable to climate effects on their quality including fruits, vegetables, tree nuts, stimulants, and herbs. However, our review on agroecological strategies to mitigate effects on crop quality highlighted a major gap in the literature and highlights the need for future research to assess the potential of variable management to buffer climate effects on quality parameters. Agricultural diversification (Schwendenmann et al., 2010; Vandermeer et al., 1998; Lin, 2011; Yachi and Loreau, 1999; Altieri, 1999) is emerging as a promising strategy for climate resilience more broadly and may also be a potential strategy for mitigating impacts on quality parameters (Ahmed et al., 2014a).

Given the lack of studies examining the effects of agroecological management to buffer impacts on crop quality, we present a socio-ecological framework that can be adapted by other researchers and natural resource managers as a way to approach feedbacks between crop quality, consumer responses, and agroecosystem management. Our integrative framework has tremendous applicability in the emerging area of nutrition-sensitive agriculture for addressing food security issues through the management of climate-resilient agroecosystems focused on the cultivation of high-quality crops that support high quality diets. This framework can further be especially useful for the agricultural marketing strategy of *terroir* to discern and promote agricultural products on the basis of production characteristics including agroecological management and geography. The development, application, and dissemination of such a socio-ecological systems framework that focuses on climate effects on crop quality and farmer responses is a step towards prioritizing such research. This framework can be applied to collect evidence to inform the design of climate-change resilient food systems focused on management of crop quality and other ecosystem services towards promoting environmental and human wellbeing.

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Contributions

- Contributed to conception and design: SA, JRS
- Contributed to conducting literature review and summarizing findings: SA
- Wrote the manuscript: SA, JRS
- Contributed revisions to the manuscript: SA, JRS
- Approved the submitted version for publication: SA, JRS

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Competing interests

We have no competing interests.

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