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Adapting a social-ecological resilience framework for food systems

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Abstract The purpose of applying social-ecological resilience thinking to food systems is twofold: first, to define those factors that help achieve a state in which food security for all and at all scales is possible and second, to provide insights into how to maintain the system in this desirable regime. However, the resilience of food systems is distinct from the broader conceptualizations of resilience in social-ecological systems because of the fundamentally normative nature of food systems: humans need food to survive, and thus, system stability is typically a primary policy objective for food system management. However, society also needs food systems that can intensify sustainably, i.e., feed everybody equitably, provide livelihoods, and avoid environmental degradation while responding flexibly to shocks and uncertainty. Today's failure in meeting food security objectives can be interpreted as the lack of current governance arrangements to consider the full and differential dimensions of food system functions—economic, ecological, and social—at appropriate scales: in other words, the *multifunctionality* of food. We focus on functional and response diversity as two key attributes of resilient, multifunctional food systems, respectively, the number of different functional groups and the diversity of types of responses to disturbances within a functional group. Achieving food security will require functional redundancy and enhanced response diversity, creating multiple avenues to fulfill all food system objectives. We use the 2013–2015 drought in California to unpack the potential differences between managing for a single function—economic profit—and multiple functions. Our analysis emphasizes how the evolution of the Californian food system has reduced functional and response diversity and created vulnerabilities. Managing for the resilience of food systems will require a shift in priorities from profit maximization to the management for all functions that create full food security at multiple scales.

Keywords Food systems · Resilience · Social-ecological systems · Diversity · California

Introduction

Growth and stability in the global food system undergirded public policy and development interventions for most of the twentieth century, with considerable success. Aggregate food output outpaced population growth; famines have gradually become less frequent, and physical and economic access to food has generally increased (FAO, IFAD, and WFP 2013). The food system challenges of the twenty-first century, however, have led some scholars, analysts, policy makers, and citizen groups to question whether the principles and objectives that shaped the food system of the twentieth century need revision. First, a defining challenge of the current era—climate change—has demonstrated that the broad agro-climatic parameters under which food production takes place are by no means stable, as elementary geography might have us believe. This conclusion has only been reinforced in the recent report of the "Impacts, Adaptation and Vulnerabilities" working group in the 5th Assessment Report of the IPCC (IPCC 2014). Second, climate change is taking place on top of an

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already significantly degraded resource base in which the availability of quality soils, water resources, and other essential inputs into production processes is threatened (Rosegrant et al. 2009). Third, the rapid pace of industrialization, market integration, and consolidation in global food systems has greatly enhanced the connectivity and interdependence of lengthy food supply chains and the relationships of food chains with other industries—such as that of energy—while typically concentrating key resources (technology, research and development, distribution channels, marketing) in fewer hands (Clapp 2011; Lang 2003). Fourth, while nutritional deficiencies and food access remain challenging in many parts of the world, new issues have emerged associated with the maintenance of food quality and safety, exacerbated by problems in transparency, convoluted and long supply chains, and the volume of information that must be processed and evaluated by consumers (Marsden et al. 2000; McMichael 2006). Finally, in the modern era of such long supply chains, food and agriculture concerns have been governed separately: production, consumption, distribution, processing, and waste management have been considered as separate concerns with distinct actors, interests, and institutional relations, yet disturbance or crisis on one domain has significant repercussions in others. Similarly, rural interests and production issues are not always explicitly tied to the dynamics of urban areas, although urban areas are where consumers, industry, policy, and wealth and finance are increasingly concentrated (Lerner and Eakin 2011).

All of these challenges have underscored the *systemic* and *dynamic* nature of food and agriculture. Given the significant uncertainties, risks and interconnectivity associated with the future of food, new organizing concepts and frameworks are required. *Resilience*, the topic of this symposium, is one such concept that has gained significant traction in a diversity of fields and policy domains. Multiple academic sources are now arguing for such an integrated approach to human-environment interactions for food systems in the face of current global economic and environmental change and the risk of disruption to food supply (Fraser et al. 2005; Sundkvist et al. 2005; Thompson and Scoones 2009), while there has also been movement towards incorporating resilience into development policies and programs focusing on food security and livelihoods (FAO 2014). Nevertheless, resilience has been slow to be adopted in food system policy and planning, perhaps in part due to the entrenched sector and industrial divisions in food system activities and outcomes.

In this contribution, we introduce resilience as it has been conceptualized in communities of scholars and practitioners focusing on social-ecological system change. We argue that while the social-ecological definition of resilience has an important role to play in increasing the sustainability of food systems, some evolution of its terminology is required to address the engrained normative judgments related to food systems. We build our argument from a critical analysis of the applicability of the concept to food systems and through identifying the attributes of resilience that are most important in the food system context for increasing sustainability. We then apply this logic to global context and US food systems to highlight potential contributions of an adapted resilience framework by examining the impacts of the current drought on Californian food systems. We conclude with an assessment of some of the primary challenges as well as opportunities in the policy arena of a resilience approach to food systems.

Social-ecological resilience

In the literature on social-ecological systems (SESs),[1] resilience is a system property. The concept emerged from the field of ecology in the 1960s (Holling 1973), with the recognition that ecosystems should be managed with the expectation of disturbance, variability, and change rather than for stability. As the concept has evolved to address a wide diversity of systems—in particular *coupled social-ecological systems*—the terminology of social-ecological resilience has also evolved, and resilience is now commonly defined as having three core dimensions (Carpenter et al. 2001):

(1) The amount of disturbance a system can absorb and still remain in the same state.
(2) The degree to which the system is capable of self-organization.
(3) The degree to which the system can build up and increase the capacity for learning and adaptation.

As a system property, resilience acknowledges the inherent couplings found between humans and nature, as seen, for example, in many coastal fishing communities, where marine resources are usually tightly integrated with the local economy and culture (Cinner et al. 2009). These interacting components form a complex and dynamic entity—an SES—where signals of disturbance in one aspect of the system, for example, technological change in a fishery, will have repercussions across other elements in the system. Within this example, technological change may affect fish stocks and therefore also potentially broader marine ecosystem dynamics and the social and political relations associated with the fishery, through direct and indirect linkages (via markets, supply chains, biochemical cycles, and the movements of people and marine life), influencing other adjacent, as well as distant, systems (Berkes et al. 2006). Resilience provides an analytical

[1] A social-ecological system is an integrated system in which humans are part of nature and therefore cultural, political, social, economic, ecological, and technological components interact (Berkes and Folke 1998).

structure through which such complex interactions and outcomes can be analyzed and potentially anticipated.

Food systems can clearly be portrayed as coupled social-ecological systems as they "incorporate multiple and complex environmental, social, political and economic determinants encompassing availability, access and utilization" and involve varying spatial, temporal, and institutional scales (Ericksen 2008:234). Framing food systems in this way means characterizing them differently to the static and linear flow model commonly used to describe, for example, a food supply chain. For example, variability should be considered the norm as opposed to stability (Holling 1973). Change can be both episodic and gradual, triggered by fast, external perturbations (such as a price spike or disease outbreak) or slower internal drivers (such as soil nutrient depletion or shifts in consumer values), which also mediate the impact and dynamic of fast perturbations.

A system exists in a particular regime or configuration. Variables within that system have thresholds, and the level of resilience within the system controls how close the system is to those thresholds. As resilience declines, the system moves closer to the thresholds and as a result, smaller disturbances will have a larger effect so that a disturbance such as a pest outbreak or changing water availability can potentially cause a threshold to be surpassed, triggering reorganization or renewal within a system and creating new opportunities for alternative regimes to become established—i.e., a regime shift (Folke et al. 2003). The new regime will have fundamentally different core functions, structures, and processes to the previous regime—the classic example being when coral reefs transition from hard corals to algal dominance, typically triggered by a combination of overfishing, pollution, diseases, and climate change (Carpenter et al. 2001; Folke et al. 2004; Holling 1973). The following section will outline the key attribute of a system that increases resilience and decreases the likelihood of regime shifts. We propose that this element is critical for managing food systems.

Diversity as the key attribute of a resilient system

In ecology, system resilience is derived from different system elements playing similar system functions across a range of spatial and temporal scales and from a diversity of different system functions operating at each scale (Allison and Hobbs 2004:3). This conclusion arose from the diversity-stability debate which has gone full circle, from the early assumption that diverse ecological communities had enhanced ecosystem stability, to May's (1973) challenge that diversity in randomly constructed communities tends to destabilize community dynamics, to the more recent empirical data of Tilman (1996) that showed diversity within an ecosystem tends to be correlated positively with plant community stability (Shear-McMann 2000). In the latter case, stability is associated with resilience in that it supports a system in retaining core functions in face of disturbance, as diversity allows a range of responses when dealing with disturbances. Diversity is therefore a key for increasing a complex system's capacity to cope with change, as a greater range of options reduces sensitivity to the loss of specific elements (Folke et al. 2004).

There are two key types of diversity—functional and response diversity. *Functional diversity* refers to the number of functionally different groups; for example, different species of plants fill distinct ecological niches within areas of a rangeland (Elmqvist et al. 2003). The occupation of different niches allows different plant species to provide dissimilar functions (i.e., taking water from different depths, growing at different speeds, storing different amounts of carbon), creating complementarity while contributing to the productivity of the rangeland system as a whole (Walker et al. 2006). Alternatively, a greater number of different species providing the same function (i.e., *functional redundancy*) results in a higher *response diversity*—the diversity of types of responses to disturbances within a functional group. Building on the rangeland example, where heavy grazing occurs and dominant grass species are removed, minor species typically replace the dominant species because they serve as functional analogues (Elmqvist et al. 2003; Walker et al. 1999). The minor species therefore carries out the same function and contributes to the maintenance of the ecosystem in the face of stresses. While leading to functional redundancy, a higher response diversity means that the there are multiple options within the system for reorganization and increased resilience (Elmqvist et al. 2003)—a key point to take forwards in our thinking with respect to the resilience of food systems.

Resilience literature tells us that managing a system for resilience should aim to increase the system's capacity to respond to disturbance through preparing for surprises and potential regime shifts. We therefore suggest that diversity is a key feature of such resilient systems. Nevertheless, this conceptualization of resilience does little to indicate the desirability of resilience in any given system state. In other words, "resilience makes no distinctions, preserving ecologically or socially undesirable situations as well as desirable ones" (Levin et al. 1998:225), i.e., resilience thinking views desirability as a normative classification created by human society while resilience itself is a descriptive system property, neither inherently desirable or undesirable. Here is where the application of resilience to food systems requires a somewhat different formulation. The following section investigates this further.

The normative nature of food systems

In the context of food systems, there are clear, desirable states and regime transformations that are simply not allowable.

Food systems are human creations for a fundamental human objective: human biological sustenance. This goal is physiologically non-negotiable. Regime shifts at multiple scales are of course possible within food systems, i.e., exits of individual farmers from an agrifood sector or sea-level rise eliminating an entire region of food production (see McMichael 2006). Nevertheless, at both a global scale and the indivisible scale of the individual human, there must be adequate production and distribution of food to maintain all human life; no regime shift that compromises that core function can be morally permitted. It is in this fundamental meaning of a *food system* that differences begin to emerge in the conceptualization of resilience between social-ecological and food systems—a different lens is required for looking at the resilience of food systems to the resilience of SESs.

The biological requirement for life defines the core *goal* of food systems—i.e., maintaining adequate food security for all humans, at all times—and the *only* permissible regime state of the food system. While there are many alternative regime states (including the regime we live in today, in which over 800 million are food insecure), these states are morally inadmissible. Thus, the purpose of applying resilience thinking to food systems is twofold: first, to define the mechanisms that can help *achieve* the state in which food security at all scales and for all is realized, and second, to provide insights into how to *maintain* the system in this desirable regime, avoiding any shifts in state that threaten that essential function.

In the most basic sense, food systems entail all the inputs, activities, and outcomes associated with food production, processing, distribution, consumption, and waste disposal (Ericksen 2008). We know, however, that food systems are far more complex than the material flows that constitute the supply chain. Food is embedded in deep and highly diverse social and cultural meanings; our food system has direct and indirect influences on a wide variety of biophysical and ecological processes and, in many ways, has been the primary driver of ecological change on the planet (DeFries et al. 2006). Food is also symbolic and political: governments have collapsed over failures in food provisioning and food system management (Davis 2001).

While food systems are social-ecological systems, they are also human-designed systems—there is a disproportionate influence and control of social elements over the ecological elements. Resilience theory indicates that in any social-ecological system, some variability, disturbance, and loss are expected to maintain system capacity for learning, innovation, and adaptability. Nevertheless, humans are unique in having the capacity for foresight and deliberate action, and self-organization in complex social-ecological systems is therefore somewhat different from that in ecological or physical systems (Westley et al. 2002). Thus when a food system is bound geographically, socially, and institutionally with food production as the main activity, often the aim is to avoid disturbance, enhance stability, and guarantee a minimum level of output so as to achieve the central goal of food security.

To avoid disturbance and manage for stability requires trade-offs. It can make the food system more rigid and less adaptable and can increase the cost of change. Furthermore, fear of negative impacts can impede experimentation and innovation. Lack of innovation and experimentation reinforces existing system dynamics, with the potential of pushing the food system into an increasingly rigid state—"a rigidity trap." An example in the US food system might be the widespread adoption of varieties of cotton that are both Bt and herbicide resistant in the 1990s. Cotton, a significant US export commodity, was devastated in the early 1990s by cotton bollworm (*Helicoverpa zea*). A genetically engineered cotton variety, containing the *Bacillus thuringiensis* (Bt) bacterium, was produced by Monsanto and approved in 1995. In the same decade, an herbicide-resistant cotton was also developed. Today over 90 % of the US-planted cotton acreage is now Bt, or herbicide resistant, or both (USDA 2013). The widespread adoption of these varieties introduced new stability in the face of annual pest and weed disturbances and thus improved annual productivity in the domestic cotton market, arguably increasing resilience in the short term. However, their adoption (and more generally the adoption of genetically modified crops) has led to a sector that is highly dependent on a handful of private corporations and a reduced suite of chemical and technological options (National Research Council 2012). Herbicide-resistant varieties, in particular, have wedded farmers to a reduced suite of weed control practices (primarily through the application of glyphosates), enhancing the risk of glyphosate-resistant weeds and reducing the response diversity of the sector (Fernandez-Cornejo et al. 2014). The increased homogenization has generated new vulnerabilities, this time associated with less flexibility of the system in face of slower-changing ecological conditions. The evolution of weeds and insects to the engineered cotton traits is now beginning to once again threaten the longer-term viability of the industry and reduces its resilience (Duke 2005; Powles 2008).

This example illustrates the essential contradictions in the contemporary food system from a resilience perspective, contradictions that now, ironically, threaten the stability of our food supply. First, while considerable amounts of energy, resources, time, and effort are being dedicated to maintain the food system in its current state, these efforts in the long term may be bringing us closer to undesirable regime shifts that threaten the viability of our food and fiber supply. Second, the very regime that we are putting so much energy into maintaining is, in fact, not achieving its stated objective and thus is ultimately not desirable. Over 800 million are food insecure; the environmental resources on which the food system depends are significantly degraded, and the capacity to produce for a future larger population is being questioned. Finally, while the food system is ostensibly being managed for stability, ultimately, it is not clear that it is stability in food access and food security that is the central goal but rather production for profit and capital accumulation. Without explicit recognition of the fundamental moral goal of food systems—i.e., food security for all—as the central normative purpose of food systems, resilience in today's food system ultimately works *against* stability and security in relation to this moral domain.

As we discuss in the next section, the concept of resilience can be used to support a more just, equitable, and secure food system. Such a system requires a *diversity of functions*: not only economic functions such as maximizing yields, financial investment, and market infrastructure but also socio-cultural and biophysical functions. Crucially, such a system would also require functional redundancy (and thus enhanced response diversity) so that there are multiple avenues to achieving the complexity of food system objectives.

Even so, the non-negotiable goal of food security for all reinforces the crucial conservative tendency in food systems that we also see in today's system. While negotiating nonlinear change, variability and adjusting to disturbance define the resilience of social-ecological systems more broadly; the potential for loss—to yields, to investments, and ultimately to human life—limits society's tolerance of volatility in food systems. Reducing vulnerability of food security to disturbance typically is measured via efforts to reduce hunger, minimize crop losses, and maintain economic productivity. These goals are often framed in moral terms and are fundamental to the social contracts that bind citizens and governments. Yet these goals also have implications for ecological processes and functions and longer-term integrity of the biophysical elements that are fundamental to our food system function. Thus, there are unavoidable trade-offs in managing for overall system resilience and in managing for the reduced vulnerability of specific system components (Eakin et al. 2009).

Multifunctionality and scale of food systems

While the core goal in more generic SESs might change at different scales (loss is tolerated locally in order to conserve broader system functions), in food systems, the core goal is (and must be) the same at all scales, from individual to global. The very definition of food security demands that *all people, at all times*, be free of hunger (FAO 2002). A result of this homogenous core objective is that there is not an optimal scale for managing food systems—they require simultaneous management to reinforce the same core objective across all scales.

For example, in today's food systems, governance (i.e., the actors and institutions involved in the implementation of food system policies) tends to occur at national to global scales and to focus largely on production and trade. Nevertheless, achieving *food security* requires concerted attention to a multiplicity of additional functions in the food system, not the least of which is food distribution and food access, as well as the cultural dimensions of food utilization and nutrition. While currently not adequately addressed in global governance, these dimensions require validation at the global scale in order to be maintained at finer spatial scales (see Eakin et al. 2010). Similarly, some ecological functions that are critical for the maintenance of the food system require global-scale management (e.g., the climate system) while others require concerted action in local contexts (e.g., soil quality). Today's failure in meeting food security objectives can be interpreted as the lack of current governance arrangements to consider the full and differential dimensions of food system functions at appropriate scales, i.e., the multifunctionality of food. Resilience thinking would indicate that we cannot assume that management at more aggregated scales will achieve the same objective at smaller scales (or vice versa); management at aggregated scales tends to diminish the importance and influence of smaller scale dynamics and drivers. This resulting tension is one of the key instabilities and motivations for food system change today.

In neglecting its multifunctional nature, the contemporary food system is particularly susceptible to surprise, shocks, and unanticipated change. In focusing narrowly on maximizing food production, changes simultaneously occurring in other key system functions (albeit at distinct rates and spatial scales)—i.e., pollination, water resource availability, nutrition, cultural preferences—inevitably reach thresholds at which they trigger shocks in food supply. These shocks are transmitted through the cross-scale (hierarchical and geographical) linkages that are so important for maintaining resilience in food systems, as in all SESs (Eakin 2010; Fraser et al. 2005). Sundkvist et al. (2005), for example, have argued that while our global food system is increasingly interconnected, critical channels of information and knowledge flows have been closed such that we are often ignorant of the origins, the impacts, and the meanings of our food consumption patterns. With an increasingly globalized food system, trends such as specialization, distancing, and homogenization weaken communication in the food chain and mask feedback signals from unhealthy ecosystems (Sundkvist et al. 2005). This lack of *feedback* inhibits learning and increases the risk of failures cascading throughout the system. Food systems are also integrally connected through biophysical networks, where, for example, seed, pests, soil, and water contaminants move across geographic boundaries to affect food production in distant places (Adger et al. 2009). This connectivity is critical as a means of transmitting signals of change and thus creating biophysical feedback loops within a complex food system.

We argue that coping with such shocks and change in the food system will be enhanced if, globally, we can re-focus the core "desired state" of the food system to one which has food security for all as is its primary objective. Such an effort would entail a new emphasis on multifunctionality: supporting the diversity of system functions, required to maintain such a desired state, as well as functional redundancy across scales, required to ensure the system has an adequate capacity to respond to any particular shock or stress.

The following section highlights the benefits of applying this adapted resilience framework to analyze the impacts on resilience of a disturbance, highlighting the multi-scale impacts while focusing on function and normative goals within the system. California is currently experiencing a severe drought, with 2014 among the driest years on record and water resources more than 20 % below average, resulting in a state of emergency being declared as of January 2014 (Office of Governor Brown 2014). Drought conditions are having a direct impact on the Californian food system, and as the current drought situation in California is still evolving, we used information from the media and grey literature to examine these conditions through a resilience framework, incorporating the adaptations as outlined above, to investigate dynamics, potential thresholds, and equity impacts. This example illustrates the problems with managing a system for too narrow objectives (profit and production) rather than the full diversity of functions at multiple scales.

Disturbances and resilience in food systems: drought in California

California epitomizes the challenges and opportunities of managing the food system for improved resilience. The state is a critical player in the US food system: its 80,500 farms and ranches produce over 400 commodities and approximately half of US-grown fruits, nuts, and vegetables, valuing $42.6 billion in 2012 (CDFA 2014a). It can be argued that the agricultural revenue for the state increased the short-term resilience of the Californian economy during the past 10 years, although by one dimension only—its economic viability. While all areas suffered during the Great Recession, the Californian impact was mediated by the dynamics of its agricultural economy (Bruno 2014).

However, as in much of the US food system, in California, the narrow focus within the food system on the economic viability of agriculture has come at the expense of food system functions such as ecological integrity, water resource sustainability, livelihood maintenance, nutritional viability, food security, and economic diversity. The result is that while there is currently a productive and agriculturally diverse regional food system, the food system as a whole remains vulnerable. This is illustrated by the current devastating drought in California, the impacts of which are transmitted through the national food system to other scales, decreasing resilience and increasing the likelihood of a regime shift that leads to a loss of not only the economic profit that has been the focus of policy but also other critical functions.

The narrow focus within California on agricultural economic productivity as the core food system objective, rather than the broader concept of food security for all, reflects a similar focus in the global and national food system. Resulting in a spatial concentration of production within the USA, this narrow focus has in turn led to *a reduction in functional redundancy across scales* (e.g., state to national). As California has excelled in horticulture and livestock production, the USA has become highly dependent on California's output and the San Joaquin Valley in particular. Currently, the California share of production is 99 % for almonds, 88 % for avocados, 91 % for strawberries, 100 % for clingstone peaches, and 95 % for broccoli and also the leading US producer for artichokes, asparagus, cauliflower, cabbage, celery, lettuce, spinach, and tomatoes (CDFA 2014b; USDA 2014a). For several commodities—particularly those commodities that require time to come into production—there are only a few alternative suppliers in the USA, although other geographic regions provide conditions suitable for production.

This loss in functional redundancy across the USA translates into a *lack of response diversity*, which then results in a rigidity in supply, translating into the possibility of price spikes from shocks to the California production system. As a result of the current drought and the tight connectivity in the globalized food system, some analysts anticipate increasing prices for the commodities in which California specializes, not only in national but also international markets (Richards 2014; USDA 2014b), although others argue that there is sufficient response diversity in the global system to mediate the local price signal, as supply changes are only one element in consumer prices.

The focus on economic viability above other functions has led to a *reduction in functional diversity* within the country and particularly within specific agricultural regions. The economic functions are underwritten by an assumption that water is abundant and the system is far from a threshold of water availability. However, if the system considered ecological functions in equal measure with economic functions, water would be priced and allocated differently. Under such conditions, it can be hypothesized that other regions in the USA would have maintained vegetable production (i.e., S.E. U.S.). However, in the current system, the national lack of functional diversity (in terms of food supply) is mirrored in California by a lack of ecological and social ambitions. For this reason, we argue for maintaining functional diversity at all scales. If food security is the core normative objective of any food system, the system must be supported by (and support) multiple social, ecological, and economic functions. In California, the narrow focus on economic viability has come at the expense of other important functions needed to maintain the food system over time. For example, although its eight counties are all in the top 12 when ranked by gross value of agricultural production (with a combined total of $32.4 billion), the San Joaquin Valley (SJV) is still one of the most economically depressed and malnourished areas in the USA (CDFA 2014b; Cowan 2005). The SJV provides a disproportionate share of the state's agricultural production and processing value (37 % in 2009) and within the SJV, 34 % of employment and 31 % of labor income are based in the agricultural and food sectors (Paggi 2011). Agriculture alone provides over 369,000 jobs (Paggi 2011).

Compared to national statistics, a significantly higher proportion of the population is food insecure in the SJV—30 % in the San Joaquin County compared to 15 % in the USA—and there is higher than average unemployment, 10 % (CFPA 2010; Coleman-Jensen et al. 2013; State of California 2014). The diversity of crops produced has, ironically, not translated into household access to diverse nutritional sources or a diversity of food distribution channels. There are limited livelihood opportunities in other sectors due to a lack of economic diversity, and economic opportunities are commonly limited to poorly paid wage laborer positions within agriculture. This has resulting impacts on food access and nutritional quality for households and fails to fulfill the function of a resilient food system in maintaining food security for all.

The drought has only exacerbated these conditions and was estimated to cause the loss of 17,100 full and seasonal jobs in the Central Valley in 2014, resulting in higher unemployment, a reduction in household income of $555 million, increasing poverty and lower food security (Alexander 2014; Howitt et al. 2014). As a result, food safety net programs (i.e., local food banks and government food subsidies), which constitute part of the limited functional redundancy in meeting food needs locally, are being stretched to the limit (Burger 2014). The outcome of such change will be a greater reliance on welfare programs, both locally and nationally as the total statewide economic cost is $2.2 billion (Howitt et al. 2014), while food prices of traditionally Californian commodities are likely to increase nationally and internationally, potentially affecting the food security and well-being of households across a large geographic spectrum.

Additionally, the focus on economic profitability as the primary goal of the food system, rather than its broader function of food security, has led to production in California becoming increasingly concentrated in high value but also high water consumptive crops and tree crops in particular. Approximately one-third of irrigated agricultural land in California is now used to cultivate nut species (including almonds, walnuts, pistachios, and pecans (Fimrite 2014)), and the shift from annual to perennial and tree crop cultivation has created a food system dependent on high water consumptive crops, which now account for 59 % of the value of crop output (USDA 2014a). Tree crops harden water demand in agriculture, as permanent tree crops are more costly to fallow than annual crop species due to the longer period it takes to establish them. Therefore, in times of drought, as California is currently experiencing, farmers' response diversity has declined: they are increasingly limited to purchasing expensive water from elsewhere, or abandoning their trees. Producers of other commodities have also been affected during the drought, but their ability to remain in production over the long term may well be higher due to the annual nature of planting their crops and flexibility in fallowing (Alexander 2014; Fimrite 2014).

In a resilient food system, the higher capacity of the system to absorb disturbance would also provide an opportunity for learning and innovation. For example, utilizing a diversity of water supplies (groundwater, effluent, surface, direct rainwater capture) or adopting innovations in water and soil resource management may enable successful drought management in some sectors and among some farmers. In all cropping systems, farmers who have already taken steps to innovate technologically with state-of-art irrigation systems and soil management practices are likely to fare better. They are the actors who utilize the knowledge within the system, undergo learning and adaptation, and so have higher levels of response diversity and therefore resilience. As noted by Keppen and Dutcher (2015) in this volume, farmers in California have, over the last decades, significantly reduced water consumption through investment in new technology and water conservation practices. In the face of severe statewide drought, some of these strategies may prove to be more successful than others.

In the meantime, however, the average water footprint of almond cultivation is 8047 m^3/t, approximately twice as much as cotton, and twenty-three to forty times more than the other main arable commodities—strawberries (347 m^3/t), tomatoes (214 m^3/t), and lettuce (237 m^3/t) (Mekonnen and Hoekstra 2010). Annually, California has approximately 53 billion m^3 of water available (combining surface water that is diverted and groundwater pumped to the surface). Of this amount, agriculture consumes 42 billion m^3—79 % of what is available—and almonds and pistachios approximately 10 % of this (Paggi 2011). Nevertheless, by some estimates, nearly half of the water consumed in agriculture also supports environmental functions (via, for example, groundwater infiltration of irrigation water), reducing the applied agricultural use to approximately 41 % of the state's resource base (Paggi 2011).

While the agriculture sector is only one of the consumptive users in the state, the response of farmers and policy makers to the challenge of drought—each with their own interpretations of the nature of the problem (see Keppen and Dutcher 2015)—can trigger significant changes in the resource base. Reduced surface water availability, due to both natural (the drought) and regulatory (the ban enforced by the State of California (Office of Governor Brown 2014)) conditions, leads to increased demand for groundwater. The net-water shortage has created additional groundwater pumping costs of $454 million (Howitt et al. 2014). Groundwater mining already occurring in California has been shown to be rapidly lowering water tables and creating subsidence, and the increased rate of abstraction during the drought will only worsen the situation, as well as further reducing the resource available for future users (Sneed et al. 2013). The use of water resources in agriculture also affects other ecological functions such as wetland function and biodiversity (Cash and Zilberman 2003). A ruling requiring the diversion of water for ecological purposes in California has become a central bone of contention between farm sector representatives and environmental groups in the current drought, further disrupting the functioning of the agricultural sector (see Keppen and Dutcher 2015). A systemic resilience perspective would caution that present-day competition for resources may mask important longer-term complementarities in use: a loss of ecological functions in California's wetlands, streams, and watersheds might over time feedback to the agricultural sector, undermining the productivity of the resource base.

We use the Californian example to highlight the deficiencies in the way current food systems are being managed. In times of disturbance, as California is undergoing, these deficiencies become clear as they begin to impact the goal we have designed the system around—economic productivity—and as such impacts are translated to multiple scales.

Discussion

Figure 1 presents a framework for evaluating food systems in relation to key resilience attributes. We suggest that any food system can be mapped onto Fig. 1 according to functional and response diversity, in relation to any particular shock or stress. Essentially, in order to achieve and maintain a food system in a desirable state characterized by core objective of *food security for all*, a society must recognize the necessary complementarities and synergies—as well as trade-offs—across temporal and spatial scales of the diverse socio-cultural, economic, and ecological functions associated with food and agriculture (*functional diversity*). Given the imperative of avoiding any adverse regime shift, *response diversity* is clearly also a critical attribute of any food system. While these attributes are not the only attributes of a resilient system, we feel they capture the importance of explicitly supporting the multifunctional nature of any food system and the critical need to avoid regime shifts in food systems that compromise the food security objective, now or in the future. However, we acknowledge that further research is required to identify and evaluate the appropriate indicators of response and functional diversity in relation to specific shocks and stressors to which systems are exposed.

Our analysis of the Californian food system suggests that currently, it would map onto the bottom left of Fig. 1, due to its primary focus on the economic profit of agriculture and the emphasis on optimizing shorter-term economic gains, rather the multiple functionality of the food system more broadly. The resulting low response and functional diversity locally may trigger disturbances that will cascade through the national and potentially international food system. The full impact of the current drought will not be apparent for some time; nevertheless, given the fragility of some subsectors in the agricultural economy and chronic problems of employment and food insecurity, the legacy of the drought might be significant.

Hypothetically, if California's food system was managed with a core goal of food security, there would be a greater recognition of the complementarity of ecological, social, and economic functions, increasing sustainability (provision of resources for future generations) and reducing the sensitivity to shocks. While this would mean drought events would have an impact, and potentially a severe one, the impact would be mediated by a foundation of humane treatment, a well-fed and food secure workforce, investment in key ecological and social services and processes, diversified local economies within the Central Valley and California, and an increased functional redundancy at the national scale.

It is important to note that California already has a wealth of resources that could be mobilized to support a more resilient system based on a fundamental goal of food security for all. California has long led the nation as a source of innovation in alternative agriculture. The University of California has internationally celebrated programs in sustainable agriculture and agroecology, and California has led the way for the nation in relation to alternative food distribution and market systems (community-supported agriculture, farmer's markets, food hubs) and organic production (representing 19 % of all certified farms and 13 % of national organic acreage (Klonsky 2010)). While these innovations may or may not increase response diversity in times of crisis, collectively they address different values and priorities in the food system and emphasize different social-environmental relationships, which can increase the likelihood of creative solutions to seemingly overwhelming challenges. It is possible that as a result of this drought event, the relative success of some production systems over others will trigger system-level learning. Such learning would encourage a positive form of regime shift: sector-wide, to more efficient water resource practices, improved food access, and economic security, enhancing overall resilience. As California seeks to improve its resilience in future droughts, it will be critical to understand how such innovation and learning can be encouraged through institutional arrangements and how learning can be disseminated across the food system.

Applying a resilience perspective should highlight the importance of diversity within the food system and lead

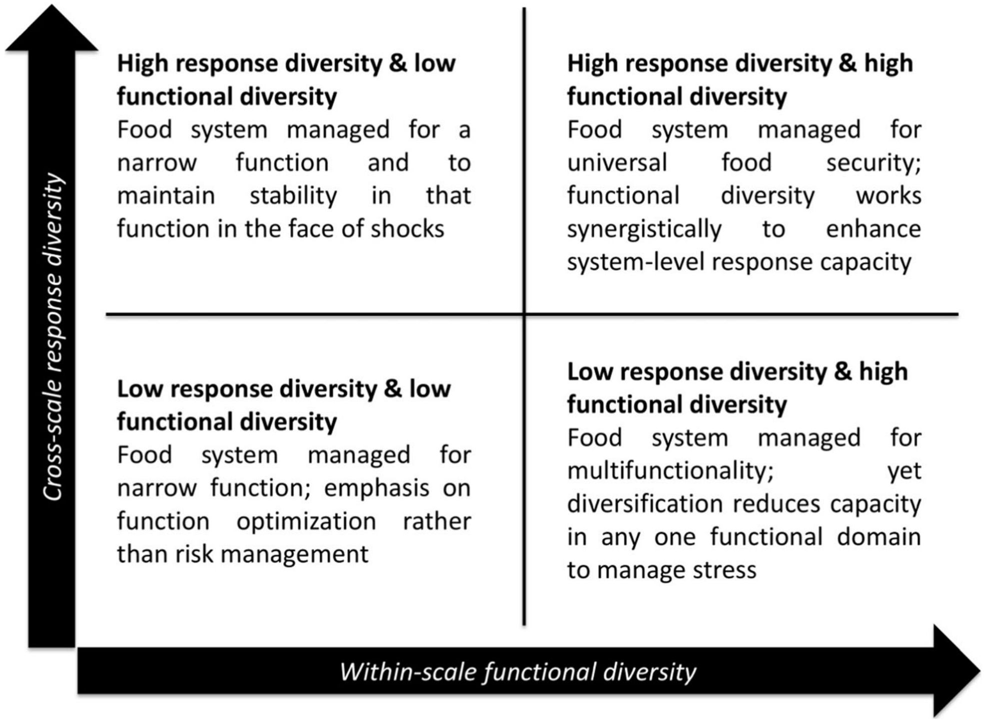

Fig. 1 A framework for assessing the response and functional diversity of food systems

managers to question the longer-term value of managing for more narrow functions such as yield optimization or economic efficiency. While human loss is unacceptable, resilience demonstrates the importance of tolerating some losses, redundancies, and inefficiencies in shorter temporal scales in support of maintaining system integrity at all spatial scales and over the long term. Agroecologists and many peasant farm communities, for example, have long recognized the value in tolerating some damage to crops and harvests in exchange for more robust crops, higher aggregate agro-biodiversity in the farm, and less inter-annual volatility in production (see Altieri 1989; Morales 2002).

The importance of response and functional diversity in systems also suggests that policies supporting the concentration of production geographically on the basis of assessments of comparative advantage and agro-climatic optimums (which, due to climate change, are also changing) may be misguided. While principles of comparative advantage may work well in enhancing economic efficiency, particularly in non-crisis years, there are trade-offs in terms of robustness to disturbance. Without some degree of redundancy, the loss of one critical system component can trigger dramatic change in system dynamics. This is true in relation to agro-biodiversity at the farm level, diversity of nutrients in household diets, diversity in food supply sources and distribution networks for cities, and the diversity of modes of production, inputs, and economic strategies across all dimensions of food system activities.

A resilience perspective advocates for neither complete connectivity nor isolated self-reliance, nor does it advocate for change over stability, or loss over conservation. Rather, a resilient food system recognizes that all of these attributes are essential for maintaining system function, learning, and adaptation. The challenge is to achieve the appropriate balance among these attributes at all scales and for all functions so not to compromise the fundamental moral obligation to ensure food security for all.

Conclusions

A resilience framework creates an integrated approach when studying drivers in food systems that stand to disrupt equitable food supply. We argue that managing for the resilience of food systems will require a shift in priorities from profit maximization to the management for all functions that result in full food security at multiple scales. Enacting such management will require enhanced attention to multifunctionality and the acknowledgment of the importance of temporal scales as well as spatial scales in thinking. Multi-scalar thinking is particularly relevant to maintaining or building up the functional and response diversity necessary to create food security—ecological, infrastructural, social—and these need to be maintained over long periods of time under conditions of high variability.

However, there are no easy answers regarding maintaining resilience in food systems, and attempting to do so raises multiple challenges—how do we increase the opportunities for learning and experimentation and avoid pitfalls associated with over-specialization? Can the food system be redesigned to value longer-term resilience even if this entails tolerance of some loss and inefficiency? While multifunctionality is desirable, at what point does the maintenance of some functions come at the expense of others? Given the connectivity in the global, national, and even local food systems, at what scale should food systems be governed? How do we maintain connectivity while not increasing vulnerability?

Despite these persistent challenges, we believe that there is a benefit to viewing food systems through a resilience lens. Acknowledging disturbance inevitably leads us to design systems that are more adaptable and include greater response diversity so there are more fluid substitutions in times of disturbance. And finally, acknowledging impacts across multiple scales requires us to understand that food systems are embedded in multiple values. Food is not simply an economic commodity but a moral one and non-substitutable. The current focus on the singular economic value of food is the basis for the current disconnect in management of food systems. This normative dimension of food systems is what sets it apart from the broader domain of social-ecological systems. Adaptive resilience to the unique attributes of human food systems enables us to consider the critical importance of diversity, the moral foundations for management, and the temporal trade-offs that are so critical for sustainability.

Conflict of interest The authors declare that they have no competing interests.

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