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Metropolitan foodsheds: a resilient response to the climate change challenge?

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Abstract The twenty-first century challenges of climate change and resource scarcity bring a new urgency to the widely recognized sustainability challenges of the US food system. Environmental and social impacts associated with the geographic concentration and specialization in production, processing, and distribution that accompanied industrialization of the US food system have degraded our nation's capacity to adapt to changing climate conditions. A consensus is emerging in sustainable food system scholarship that two fundamental changes—a transformation of production methods from industrial to sustainable and a transformation of food system geography from regional specialization to regional diversity—should enhance the resilience of the food system to climate change. A review of the literature suggests that transition to a nationally integrated network of sustainable metropolitan food systems ("metropolitan foodsheds") would improve climate resilience by enhancing three key qualities associated with resilience in social-ecological systems—diversity, modularity, and balanced accumulation of capital assets. These qualities promote the capacity of a system to respond, to recover, and to transform in ways that reduce damaging effects and take advantage of opportunities created by change. Using a set of behavior-based resilience indicators in a review of case study research, this article examines the general resilience of sustainable production and supply chain systems. Sustainable production systems managed by award-winning sustainable food producers expressed all of the behaviors of a resilient system and demonstrated remarkable resilience to weather variability and extremes. These producers attributed the climate resilience of their farms and ranches to high-quality soils, planned biodiversity, and diversified marketing. Like many sustainable producers, these farmers and ranchers not only produce crops and livestock, they also participate in processing, distribution, and retailing. Resilient behavior was also expressed in sustainable supply chains developed by networked community cooperatives and through government investment in a large nonprofit food terminal. As recent food system planning projects in the USA illustrate, there is growing recognition of the potential sustainability and resilience benefits of regional food systems designed to develop positive relationships between the metropolitan core and surrounding areas. We can begin now to shift public support for a transition to more diversified production, to develop regional food system infrastructure, and to conduct comprehensive research to refine resilience indicators and develop food system performance metrics to guide a transformation of the US food system to a more sustainable and resilient future.

Keywords Agriculture · Food system · Sustainability · Resilience · Climate change · Metropolitan foodshed · City region · Megaregions

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Introduction

The US food system, remarkably resilient over the last 150 years, faces unprecedented challenges as we enter the twenty-first century. Climate change, declining quality and quantity of natural resources, highly specialized and concentrated production, supply, and marketing chains, reliance on external or distant resources, and subsidies which mask environmental degradation have been identified as key challenges to the sustainability and resilience of the US food system (Ericksen 2008; National Research Council 2010; Walthall et al. 2012; Marten and Atalan-Helicke 2015). In the last decade, federal and state governments, businesses, and civil society have begun to invest in research and planning projects focused on developing effective climate change adaptation strategies, and sustainable food system planning has begun to incorporate resilience considerations (e.g., King 2008; Resilient Cities Team 2013).

Sustainable development has been widely recognized as a promising strategy for discovering solutions to twenty-first century challenges in the USA and globally (McIntyre et al. 2009; National Research Council 2010; Giovannucci 2012). Sustainable agriculture and food systems[1] exhibit many of the key structural and functional qualities that contribute to the resilience of social-ecological systems. Sustainable farming systems promote the ecosystem services that form the foundation of a resilient social-ecological system (Kremen et al. 2012; Lengnick 2015a). Healthy ecosystem processes, such as the capture and flow of solar energy and the cycling of water and other materials, enhance the local self-reliance of the system by reducing the need to import energy and materials and to export waste. Short supply lines promote food system resilience by reducing the impact of disturbances and shocks that can be transmitted through global supply chain networks. The multiple environmental, social, and economic benefits produced by sustainable food systems promote the accumulation of balanced capital assets—natural, human, social, financial, and technological—needed to support the adaptive capacity of the system. Sustainable agriculture also offers an unprecedented opportunity to mitigate climate change while increasing agricultural productivity worldwide through the use of regenerative agricultural practices (Beebe 2010; Rodale Institute 2014).

This paper explores the potential climate resilience benefits associated with a structural transformation of the US food system to a nationally integrated network of regional sustainable food systems oriented to major metropolitan areas: metropolitan foodsheds. It begins with a review of recent literature on food system sustainability and resilience and discusses a convergence on the regional scale as a promising strategy for cultivating food system resilience in the face of climate change and other challenges. Then, the paper presents case study research utilizing a set of recently proposed behavior-based agroecosystem resilience indicators to explore the climate resilience of sustainable farming systems and food supply chains in North America. Finally, the paper presents some concrete examples of regional food system development already underway in the USA and discusses some potential benefits and challenges of reorienting US food production to metropolitan regions.

Food system sustainability and the regional scale

In the latter half of the twentieth century, a growing awareness of the environmental and social harms of an increasingly specialized and concentrated US food system led to a search for solutions that emerged as the sustainable agriculture and food system movement. This work focused on understanding the sustainability challenges created by the changing structure, function, and purpose of the US food system during a period of intense industrialization and globalization near the end of the twentieth century (National Research Council 2010).

In the early 2000s, sustainable food became a new focus for physicians, dieticians, public health specialists, and municipal planners who brought more attention to land use, transportation, and economic development issues and advocated for increased access to healthy, nutrient-dense foods (Hodgson 2010; Koliba et al. 2011). By mid-decade, civic agriculture emerged as a new conceptual framework for community-based food systems (Lyson 2004). Civic agriculture extended the concept of sustainable agriculture to emphasize the potential of agriculture and food systems to produce multiple benefits in support of the social well-being of communities—particularly the capacity of local food production to restore local economies and revitalize democratic participation.

As sustainable food research matured and the results of empirical research on local food systems began to accumulate, some of the sustainability benefits assumed by the proponents of local food systems came into question (Peters et al. 2009). Food travels primarily by freight truck, where "over the road" (OTR) is more efficient than short haul and "less-than-full load" (LTL) freight movements. The inefficiencies in moving food shorter distances create market disincentives for local food, either in high transportation costs to shippers or in high cost of goods to wholesale buyers. LTL for local foods, where

[1] Although no simple typology or set of categories can capture the complexity of the farming systems used in US agriculture, we use the terms *sustainable* and *diversified* to refer to farming systems that emphasize the use of natural processes within the farming system, often called "ecological" or "ecosystem" strategies, which build efficiency (and ideally resilience) through complementarities and synergies within fields, on the entire farm, and at larger scales across the landscape and community. Such farming systems represent a major departure from the key features which characterize *industrial agriculture*: large size combined with a high degree of specialization, reliance on off-farm and synthetic inputs, and the production of commodities under contract to food processors and handlers. A *food system* is the complex set of actors, activities, and institutions that link food production to food consumption. Food systems differ from farming systems in that the primary focus is beyond the farm gate (National Research Council 2010).

farmers are not sufficiently aggregating product to sell at scale, is especially inefficient (Day-Farnsworth and Miller 2014). Limited research into energy use found that local food systems could be more energy-intensive than food sourced regionally, nationally, or in some special cases internationally, and it became clear that although food sourced locally traveled fewer miles, the environmental impacts of food transport are complex and food miles alone are not a useful indicator of sustainability (Hill 2008).

New concerns also arose about an erosion of values as the local food movement gained momentum. The introduction of food hubs and other means to increase the volume of local food moving through local markets raised concerns that local food was being sacrificed at the altar of cheap food and motivated reminders that local food is defined by more than just geography (Bellows and Hamm 2001; Born and Purcell 2006; Delind 2010; Perret 2013). Local food produces many social benefits that may be lost as the distance between the producer and consumer increases. For example, recent research suggests that the climate resilience benefits often associated with local food systems may not survive scaling up because introducing distributors erodes the social capital cultivated by direct markets (Furman et al. 2013).

Nevertheless, Michael Pollan captured the zeitgeist of many leading thinkers in the sustainable food movement when he proposed sustainable regional food systems as a comprehensive solution to the triple challenge of peak oil, climate change, and public health facing our nation (Pollan 2008). He identified the sustainability challenges of food systems in the USA and abroad as key public health and national security concerns. He warned that little progress would be possible on the nation's public health, energy independence, or climate change challenges without the recognition of their connections with the industrial food system. Pollan's "Sunfood Agenda" called for federal policy changes to resolarize agriculture through a transition to sustainable practices, reregionalize food systems by rebuilding regional processing and distribution infrastructure, rebuild America's food culture by reintroducing children to the culinary arts and traditions.

In the years since the Sunfood Agenda was proposed, a new awareness of climate change, coupled with the global financial and oil shocks, brought additional urgency to the quest for changes to enhance the sustainability and resilience of the US food system. The regional scale has continued to be a focus of this work as major US cities and intrastate regions, several states, and a number of multistate collaborations have explored regional food system sustainability, assessed the productive capacity of regional food systems, and developed plans to promote food system resilience (Kelly nd).

Regions have a number of qualities that, taken together, offer unique opportunities for cultivating food system sustainability and resilience (Liverman and Ingram 2010). Human understanding of the physical world is based on biophysical patterns defined at regional scales, for example, an ecosystem or a watershed. Strong cultural dimensions often arise at a regional scale, and useful units for private and public sector governance are often found there as well, although political boundaries can complicate regional collaboration. Regional populations tend to concentrate in cities and to have more influence at the national scale than local populations. Regional populations, through democratic participation, have a voice in setting national policies and programs that can be used to promote national food system sustainability and resilience goals.

Clancy and Ruhf (2010) describe an ideal regional food system as one that returns multiple social, economic, and environmental benefits to all the regions' inhabitants while contributing "significantly" to their food needs. Much of the production, processing, and distribution takes place within the region and at multiple scales. They go on to discuss the importance of complementary relationships between local and regional food systems and the unique contribution of regional food systems to food resilience at both the local and the national scale. It is the complex network of complementary relationships within and between local and regional food systems and the national food system that enhances the food resilience throughout the system as a whole. Ideal regional food systems are self-reliant, not self-sufficient.

The expanded land base of regional agriculture, compared to local food systems, offers a number of benefits to sustainability and resilience along four dimensions—food supply, natural resource management, diversity, and economic development (Clancy and Ruhf 2010). Historically, regional food systems supplied a significant proportion of the local food supply, and recent research suggests that many regions in the USA could still do so (e.g., Peters et al. 2012; Ruhf 2015; Zumkehr and Campbell 2015). Regional approaches to the management of the natural resources upon which food production depends—particularly land, water, and soil resources—have a long history of proven effectiveness. Regional food systems can support a more diverse mix of agricultural production systems and usually have a more diverse population base. The economic benefits associated with short supply chains can still be realized at the regional scale, but greater efficiencies in food storage, processing, and distribution can be gained through the cooperative development of regional food system infrastructure. Finally, a regional focus links urban markets and rural production areas, offering an opportunity to include intraregional interactions such as trade, development, transportation networks, and other system elements that will become more important as urban areas continue to increase in significance in coming years (Liverman and Ingram 2010).

The climate resilience of food systems

The vulnerability of a food system to climate change is a function of the exposure of the system to climate change effects, the sensitivity of the system to those effects, and the adaptive capacity or ability of the system to cope with or adjust to climate effects and moderate potential damages and take advantage of opportunities created by climate change (Lengnick 2015b). Adaptive capacity provides the conceptual link between climate change vulnerability and resilience. Resilient systems have high adaptive capacity. Systems with high adaptive capacity are resilient.

Although decisions about how best to enhance the adaptive capacity of a farm or food business ultimately lie with individual owners and managers, institutions, governance, and community characteristics create barriers to, and opportunities for effective adaptation (Marshall et al. 2009; Jones et al. 2010). Four essential community characteristics appear to explain why some communities are better able than others to adapt to the uncertainties associated with climate change: flexibility, the capacity to reorganize, the capacity to learn, and an asset base that offers a diversity of options within each asset type and equal access to all types of assets, as described in Table 1. These characteristics are applicable across different scales (individual, family or business, community, region, or nation) and community types (rural, periurban, or urban) and are commonly applied to climate change vulnerability assessment and adaptation planning worldwide (Noble et al. 2014).

The key qualities of resilient systems

Over the last decade, resilience has become increasingly featured as a goal of businesses and organizations, product marketing, and public policy. Resilience science has origins in a diverse set of disciplines, including engineering, ecology, psychology, human health, business, and disaster management (Walker and Salt 2012). Engineering concepts of resilience focus on design for tolerance to a predetermined range of disturbance or stress. This type of resilience, called robustness, is useful in situations when the threats to the system and the system's response to those threats can be reliably predicted. The resilience concepts developed in ecology, psychology, and disaster management are more relevant to food systems, because these disciplines have developed methods to assess, monitor, and manage resilience as a dynamic quality of complex adaptive systems.

Resilience science is well-grounded in ecological theory and has a long history of development in natural resource management (National Research Council 2010). More recently, this work has been extended to the study of climate change vulnerability and adaptation in many ecological and social systems, including agriculture and food systems. The design and management of resilient social-ecological systems seeks to promote three key system behaviors: *response capacity* (ability to respond quickly and effectively to buffer disturbances), *recovery capacity* (ability to quickly restore the system after damage), and *transformation capacity* (ability to transition the system to a new identity when the capacity to respond or recover is exceeded or transition is desired) (Walker and Salt 2012).

Because resilience involves system behavior, defining the scale and identity of the system under consideration is an important step in assessing and managing for resilience. Although the appropriate *scale* of focus will be determined by management goals and purview, resilience considerations require keeping in mind the scales immediately above and

Table 1 Key elements of adaptive capacity in communities (adapted from Marshall et al. 2009)

Community characteristics	Description
Flexibility	The level of social, cultural, political, economic, and environmental flexibility within a community.
Capacity to organize	The formal and informal capacity to communicate clearly, develop successful adaptation plans, establish and maintain effective community organizations, make decisions based on shared values and goals, and manage community-based recovery responses.
Capacity to learn	The extent to which the capacity to organize is moderated by adaptive learning and subsequent modification of adaptation plans.
Capital assets	**Description**
Natural	Ecosystem services that provide the foundation for human livelihoods, health, food security, and prosperity.
Human	The skills, health, well-being, and education of individuals that contribute to the productivity of labor, capacity for social learning, and capacity to manage change.
Social	The reciprocal claims on others by virtue of social and institutional relationships, close social bonds that facilitate trust, cooperative action, and formal and informal social linkages that facilitate social learning and the sharing of resources.
Physical	Community infrastructure, equipment, and technologies produced with economic activities and supported by other types of capital; the built environment.
Financial	The level, variability, and diversity of income sources and access to other financial resources (subsidies, credit, savings) that contribute to individual and community wealth.

below the focal scale. This is because processes operating at these scales (for example, soil biology below the field scale or farming system complementarities above the field scale) often have a direct influence on behavior at the focal scale.

Identity refers to characteristic structure, function, and purpose of a system. For example, pasture-finished beef and cattle-feeding operations are very different in structure, function, and purpose, so they each have a characteristic identity. Most pasture-finished beef operations will be similar in *structure* (mature cows are managed to produce calves on pasture; most of their offspring are managed to market weight on pastures), *function* (energy flows into the system from the sun to pastures to cattle and is exported as beef), and *purpose* (sustainable production of beef for specialized, value-added markets). Most concentrated animal-feeding operations also share a similar structure (cattle of uniform age are produced on bare dirt lots and fed imported grain), function (fossil/solar energy, water, and nutrients imported as cattle and feed and exported as cattle and wastes), and purpose (land- and labor-efficient production of beef for commodity markets). Similarly, regional wholesale markets are distinct from national and global supply chains. Research on mid-scale farms and supply chains indicates that these businesses seek to achieve multiple goals, both business and social. They rely on strategic partnerships, transparency, and other cooperative means to optimize success (Lyson et al. 2008).

Resilience considerations bring up important questions about the *desirability* of the system, in other words, its ability to achieve a host of business and societal goals. Are there other ways to structure the system to improve performance? Can functions be managed differently to reduce costs or increase benefits? Resilience considerations also encourage the exploration of current or future events that might represent critical threats to the system's identity. If the existing system is performing well, the goal of management might well be to enhance its adaptive capacity in anticipation of the increasing uncertainties associated with a changing climate; however, if the system is not fulfilling its purpose, resilience design criteria can be used to transform the system into a new, more desirable identity. Resilience, like all system-thinking practices, encourages us to take a step back from the system, see it with new eyes, and question underlying assumptions and rationalizations (Meadows 2008). This is the transformative aspect of resilience.

Resilient systems—persons, families, farms, or communities—share three key qualities: diversity, modularity, and a balanced portfolio of capital assets (Lengnick 2015a). *Diversity*—biological, social, and cultural—supports the capacity to adjust to changing conditions, disturbances, and shocks; to invent creative solutions to novel challenges; and to capitalize on new opportunities created by change. *Modularity* in resilience science refers to system designs in which critical system functions are supported by a network of diverse local and regional resources. Modularity supports healthy natural and social resources, increases innovation capacity, and reduces the potential for local damage from disturbances in distant places. A *balanced portfolio of high-quality capital assets*—natural, human, social, financial, and physical—provides needed resources to recover from disturbance and put innovative ideas into action.

A set of behavior-based indicators developed from the literature has been proposed for the assessment of resilience in agroecosystems[2] (Cabell and Oeofse 2012). The 13 proposed indicators describe key ecological and social behaviors associated with systems that have the capacity for adaptation and transformation. Many of these behaviors are commonly observed in agroecosystems under sustainable management. Considered together, these 13 proposed resilience criteria fully address the principles of sustainable agriculture through site-specific, ecosystem-based design; the emphasis on managing ecosystem processes through planned biodiversity; the focus on the economic well-being of producers, food system workers, and society as a whole; and the recognition of linkages between the health of the production system components—soil, crops, livestock, and people—and the greater community.

Resilience thinking offers a conceptual framework particularly useful to the management of agricultural production systems under the challenges of resource scarcity and climate change. It extends sustainable agriculture management considerations with the explicit recognition that agricultural production systems, like all social and ecological systems, exist in a state of dynamic change. In addition, resilience thinking acknowledges that social and ecological systems do not operate independently but rather interact across different spatial scales and through time in highly complex and sometimes surprising ways (Walker and Salt 2012). Applied to the design and management of sustainable agriculture systems, resilience thinking practices will enhance adaptive capacity to climate change effects while furthering economic, social, and environmental sustainability goals (National Research Council 2010).

[2] *Agroecosystems* are human-dominated ecosystems managed to produce food and other agricultural products. Like all ecosystems, agroecosystems can be described in terms of key structural and functional properties that largely determine their health and productivity. The structural properties—such as species diversity, vegetative architecture, and the food supply web—describe the physical relationships between the organisms that inhabit the ecosystem. Functional properties describe the dynamic processes that capture, move, and store energy and materials in the ecosystem; regulate populations of organisms that inhabit it; and shape the development of the system over time. Because the boundary of the agroecosystem is defined by the user, energy flow and material cycling can be explored at a diversity of nested scales—a field, a whole farm or ranch, or even an entire food system. In each case, the physical components of the agroecosystem can be defined and measured; the interactions between components investigated; and emergent properties like health, profitability, sustainability, and resilience explored (adapted from Gliessman 2007).

Agricultural resilience is being actively explored by researchers working at a variety of scales: on the farm (e.g., Hendrickson et al. 2008; Darnhofer et al. 2010; Marshall 2010; van Apeldoorn et al. 2011), in rural communities (e.g., Nelson et al. 2010), in food systems (Hodbod and Eakin 2015; Ruhf 2015; Tapiola and Paloviita 2015), and across regions (e.g., Allison and Hobbs 2004; Easterling 2009; Kenny 2011).

Are sustainable food systems climate resilient?

Although empirical evidence is sparse, sustainable agriculture and food systems appear to have many qualities that are consistent with resilient systems. Sustainable farmers and ranchers typically manage much greater biodiversity, employ more people in better jobs, and circulate more dollars in the regional economy (Lyson 2004). The diversified production systems typical of sustainable farms and ranches reduce the need for fossil-fuel energy, water, pesticides, and synthetic fertilizers and typically produce less waste (Kremen and Miles 2012; Liebman and Schulte 2015). Because sustainable producers seek to meet both environmental and social goals, practitioners place a priority on producing high-quality natural resources—soil, water, air, biodiversity, and fresh, whole, nutrient-dense foods. They contribute to the environmental and social well-being of the communities that they call home (Pimentel et al. 2005).

Recent research to understand the climate change perceptions and adaptations of producers in the USA suggests that many farmers using industrial practices recognize the resilience benefits of sustainable agriculture practices, such as managing for high soil quality and diversification. A large survey of commodity crop producers (corn, soybeans, wheat, rice, cotton) in Mississippi, Texas, North Carolina, and Wisconsin found that these farmers would be most likely to diversify crops, buy more crop insurance, modify lease arrangements, or exit farming if weather variability and extremes intensify as projected in coming years (Rejesus et al. 2013). Focus group research with 150 Maine farmers representing seven major commodity groups—potato, dairy, blueberry, vegetable, apple, beef, and nursery plants—found that these farmers are responding to more variable weather and extremes by increasing crop diversification, adding drainage and irrigation systems, increasing physically protected growing areas, and using ecological production practices that build soil quality to improve cropping system capacity to buffer weather extremes (Jemison et al. 2014). Case study research with 15 organic and conventional dryland (nonirrigated) grain producers in Montana found that the most common adaptation to more frequent and extreme drought was to diversify crops, build soil quality, and increase profitability by reducing costs and/or selling into high-value direct markets (Stephens 2015).

National case study research found a multitude of climate resilience benefits associated with the environmental, social, and economic conditions cultivated by 25 award-winning sustainable producers.[3] Some key natural resource conditions that enhance climate resilience are those that buffer weather variability and extremes, such as has high soil quality and diversified production systems. A key social condition is the high social capital generated by direct relationships with consumers and the potential for local innovation created through farming and ranching networks that share place-based knowledge about sustainable agriculture and food system practices. Key economic conditions are those that increase profitability, such as on-farm processing, and integration into diverse high-value local and regional supply chains.

These producers also recognize the supportive relationships between agroecosystem conditions that serve to enhance farm resilience. For example, product diversity and novelty in the shape, size, color, and flavor of vegetables and fruits is not acceptable to commodity wholesale markets but is valued in direct markets such as community-supported agriculture (CSA), farmers' markets, and high-end restaurants. Sustainable agriculture practices such as planned grazing restores degraded soils and rangelands and produces a high-value product—grass-finished beef—that is in demand in wholesale and retail markets nationwide. Using the agroecosystem resilience indicators presented in Table 2, we examine four of these cases in detail to explore the contribution of high soil quality, planned biodiversity, and diversified direct marketing to selected climate change exposures currently challenging many US producers: extreme drought, warmer winters, and more variable seasonal patterns of temperature and precipitation.

Biodiversity enhances resilience to drought and flooding in California

Full Belly Farm sits on the western edge of a slow-moving catastrophe. Five years of extreme drought have tested the resilience of the industrial agriculture that dominates California's Central Valley. In 2014, California agriculture experienced the greatest absolute reduction in surface water allocation in history, idling more than 430,000 acres of agricultural land and costing producers about 1.5 billion dollars in total direct economic losses (Howitt et al. 2014; Keppen and Dutcher 2015). Most of these losses were sustained by growers in the Central Valley. While many vegetable growers in the region had to take land out of production, invest in new wells, or transition to higher value tree crops in an attempt to stay in business, Full Belly Farm remained productive and profitable. High soil quality, biodiversity, and profitable direct markets appear to be key to the farm's resilience to the continuing drought and more frequent winter flooding that plagues the region.

[3] These case studies are reported in detail in Lengnick 2015a.

Table 2 Indicators of resilience in agroecosystems

Resilience indicators	Description of associated agroecosystem behaviors	Associated sustainable food system behaviors
Ecologically self-regulated	The capacity of the ecological components of the agroecosystem to organize and create relationships that generate ecosystem services with minimal management intervention. Self-regulation is a promoted management that enhances the ability of plants and animals in the agroecosystem to freely engage in different relationships in their own self-interest. Self-regulating ecosystem processes provide balancing feedbacks that maintain the identity of the agroecosystem despite changes in internal and external conditions.	Diversified production and processing systems and seasonal diets aligned with local ecological conditions.
Functional diversity and response diversity (redundancy)	The capacity of the different species or assemblages of species that inhabit the agroecosystem to produce different kinds of ecosystem services over a wide range of conditions. Functional diversity describes the number of different ecosystem services produced by the agroecosystem. Response diversity describes the capacity of the agroecosystem to produce a specific ecosystem service—for example, nitrogen production or pollination—across a wide range of conditions. Response diversity describes the redundancy in ecosystem services. Redundancy may decrease a system's efficiency, but it also buffers the system from disturbance by providing multiple strategies for the delivery of crucial services.	Diversified production systems that integrate cover crops, annual and perennial crops, livestock, and wildlife; cultivation of healthy energy flow, water and mineral cycles, and community dynamics; variation in cultivars for food crops and in animal breeds; on-farm waste recycling; alternative energy production; diversified marketing strategies; diverse retail outlets such as groceries, restaurants, institutional food service; different regional sources for specific foods; multiple transportation modes and routes for food distribution; multiple food storage locations; public policy promoting food system diversity.
Spatial and temporal diversity	The degree of heterogeneity across the landscape that serves to support ecological self-regulation, functional diversity, and response diversity by providing opportunities for the formation of diverse biological relationships and linkages across space and time.	Manage farm landscape to include distinctly different small-scale ecosystems present in production fields, pastures, edges, and natural areas that change over time; policies to support landscape diversity across production regions; specific foods available and eaten seasonally.
Appropriately connected	The number and quality of ecological relationships within the agroecosystem. Many weak (i.e., not critical to function) connections are favored over a few strong (i.e., critical to function) connections. Agroecosystems that rely on a few strong connections for critical resources tend to be less resilient to events that disrupt those connections; however, there is evidence that too many weak connections may also degrade resilience through increased inefficiency (Goerner et al. 2009).	Crop diversity and optimization of ecosystem services such as pollination, soil cover, wildlife habitat; farm design that encourages functional and response diversity; cooperative supply chain relationships with multiple producers, suppliers, markets, and farmers.
Exposed to disturbance	Behaviors that promote agroecosystem response and recovery capacity through frequent, small-scale disturbances that do not exceed the coping capacity of the agroecosystem. Disturbance makes resources available for reuse; promotes learning and experimentation; enables the selection of robust plants, animals, production practices, and agroecosystem configurations; and encourages the emergence of novel relationships.	Crop rotation; intensive grazing; biointensive integrated pest management; adaptive management: community-based, participatory farm and food system research.
Coupled with local natural capital	The capacity of the agroecosystem to function largely within regionally available resources increases the modularity and appropriate connectedness of the agroecosystem and reduces degradation of other regions caused by the import of natural resources or the export of waste.	Manage soil quality and biodiversity to maintain healthy regional energy, water, and mineral cycles and promote plant and animal health; little need to import energy, water, nutrients, and labor or export waste.
Socially self-organized	The people in the agroecosystem are free to organize and engage in productive relationships and site-specific innovation within the agroecosystem. Self-organizing agroecosystems promote the accumulation of the natural, human, social, physical, and financial capital needed for self-regulation, experimentation, innovation, and development and tolerate some disorder and a high degree of freedom in the system.	People organize into grassroot networks and institutions such as coops, labor unions, farmers' markets, community sustainability associations, food policy councils, community gardens, and advisory networks; food system actors participate in research and community development efforts; supply chains are based on strong communication, trust, and shared risks and benefits; community ownership of food supply chain businesses.

Table 2 (continued)

Resilience indicators	Description of associated agroecosystem behaviors	Associated sustainable food system behaviors
Builds human capital	The capacity of the agroecosystem to produce high levels of human capital through beneficial educational, economic, and social relationships. Human capital can be constructed (economic activity, technology, infrastructure), cultural (individual skills and abilities), and social (social organizations, norms, formal and informal networks, leadership, and power dynamics).	Investment in infrastructure, institutions, and governance that support community-based education, research, and development of locally owned farm and food supply chain businesses.
Reflective and shared learning	The capacity of the agroecosystem to promote the integration of local knowledge with scientific knowledge, support social learning and community tolerance for complexity and wicked problems, and spark place-based innovation.	The use of adaptive management strategies; support for peer-to-peer professional development networks; participation in community-based research and education networks; the preservation of historical records and the use of benchmarking.
Honors legacy	The capacity of the agroecosystem to recognize and take advantage of the powerful influence that past conditions and experiences have on present identity and future development. The biological and cultural memory embodied in an agroecosystem offer a rich source of place-based knowledge and experience that can be drawn on for inspiration and innovation. Trust based on past experiences enables effective collaboration, shared leadership, diffused power relationships throughout the system, and the ability to plan cooperatively for the future.	Activities that preserve, honor, and celebrate the cultural and ecological heritage of place such as the maintenance of heirloom seeds, engagement with elders, documentation and celebration of culinary traditions, and traditional food production and processing techniques.
Globally autonomous and locally interdependent	A structural organization of the agroecosystem that promotes resilience to environmental and social disturbances that are outside of local influence or control. Local interdependence promotes self-organization, modularity, and appropriate connectedness.	Diversified production, processing, and marketing systems coupled to local resources; participation in local purchasing and marketing cooperatives; smaller wholesale volumes linked to regional supply chains; local ownership of food supply chain businesses and small business viability; open communication and constructive feedback along the supply chain; sharing supply chain risks, costs, and benefits; democratic governance. Global food system challenges are addressed by families, businesses, communities, or regions.
Reasonably profitable	The capacity of the agroecosystem to produce a living wage to labor, a reasonable return on invested capital, and the financial resources needed for health care, education, family activities, retirement, and other desired activities and services.	Profitable production, processing, and distribution of food products; smooth intergenerational transfer of farms and other small businesses in the food supply chain; fair labor relations throughout the supply chain, especially with hired workers.

The twelve indicators reported in this table describe behaviors that support the capacity for adaptation and transformation in an agroecosystem (adapted from Cabell and Oeofse 2012 and Tapiola and Paloviita 2015)

Paul Muller is co-owner and production manager of Full Belly Farm, a 400-acre diversified organic farm located in the Capay Valley of Northern California just west of the Central Valley. The farm raises more than 80 different crops including vegetables, herbs, nuts, flowers, fruits, and grains and also raises chickens and sheep. The farm landscape is a diverse patchwork of annual crops, pastures and perennial orchards, hedgerows, and riparian areas managed as habitat for beneficial insects, native pollinators, and wildlife.

The ecological diversity at Full Belly Farm was intentionally designed to foster sustainability on all levels. Production goals include healthy soil, a stable, fairly compensated workforce, an engaging workplace that renews and inspires everyone working on the farm, and happy customers. The productivity of this agroecosystem is based on the use of cover crops and the integration of sheep and poultry to capture and cycle crop nutrients and water, maintain soil health, and prevent losses from pests and disease. Virtually all of the production on the farm is irrigated, mostly with water from Cache Creek, which runs along one side of the property. The farm sells to a diverse mix of direct markets in the San Francisco Bay area that includes restaurants, grocers, farmers' markets, and a 1500-member CSA. Full Belly also supports a number of educational and outreach programs to help create awareness of the importance of farms to all communities.

The resilience of Full Belly Farm arises from the spatial and temporal diversity that supports ecological self-regulation and cultivates the diversity needed to promote nutrient cycling, water conservation, and pest suppression over a wide range of environmental conditions. On-farm production and cycling of crop nutrients through the use of cover crops and the integration of livestock creates many weak connections to provide crop nutrient needs. Managing for a pest-suppressive landscape cultivates the response and recovery capacity of the agroecosystem because low-level pest disturbances are tolerated. These nutrient and pest management strategies also serve to couple the farm to local natural capital and increase the farm's autonomy from global energy and nutrient flows.

The resilience of Full Belly Farm also results from the social capital generated by diversified direct marketing strategies. Selling into diverse direct markets builds social networks that encourage self-organization and innovation both on the farm and in the surrounding community. The explicit management focus on the well-being and personal development of employees and social relationships between farm and community promotes the high-quality human capital and the reflective and shared learning needed to cultivate innovation in the agroecosystem. Although no financial information was gathered in this case study, the farm's long history of success and capacity to provide financial support for three families plus numerous full-time and seasonal employees suggests that it is reasonably profitable.

According to Paul, "water is the critical piece here in California" and water conservation has always been a management focus at the farm. Since 2010, an extended drought coupled with drier and warmer winters, longer and more variable spring and fall seasons, and more frequent heavy rainfall offer both challenge and opportunity to Full Belly Farm. Declining water supplies have made growing the cover crops—so crucial to building soil quality and providing nutrients for food crops—more challenging. Increased weather variability has made planning and conducting fieldwork more difficult by reducing the periods when work can be done without damaging soils and crops. A lengthening growing season offers opportunities to expand crop production in early spring and late fall to capture the higher prices typical of those parts of the year.

The flexibility and innovation made possible by Full Belly's diversified production system is illustrated by management response to these new challenges and opportunities. The management team has access to the full range of high-quality assets to respond to new challenges and take advantage of new opportunities. They are considering a transition to cover crops that are drought tolerant or produce more than current cover crops with the same amount of water. They are also looking at ways to use cover crop mulches to conserve soil moisture. And, they are weighing the costs and benefits of more water-efficient irrigation systems such as drip and microsprinklers. These involve significant initial investment and add management challenges because they require filtered water, which the farm does not need now.

The managers are also working to address the threat of more extreme weather events at the landscape scale. Cache Creek drains a large watershed above the farm. The fields near the creek are kept in winter cover crops to reduce soil loss in the event of a flood, which would most likely occur during heavy winter rains. The farm also actively manages riparian zones along the creek so that flood waters move over the lower parts of the farm without damaging production areas.

Full Belly Farm enjoys the resilience cultivated by a diverse landscape mosaic and rich social network typical of many sustainable farming systems. The extraordinary biological diversity produces healthy high-quality products, promotes soil health, reduces the need for purchased inputs such as fertilizers and pesticides, conserves water, and protects the farm from flooding. Attention to creating positive social and economic relationships on the farm and within the local community through direct marketing, educational programs, and the development of the farm's human capacity produces the social capital and the financial resources needed to support a response, recovery, and transformation capacity that has sustained Full Belly Farm through changing environmental and social conditions for more than 30 years.

Diversified direct markets enhance resilience to increased frost risk in Colorado

Variable spring weather has always been a challenge to tree fruit growers because of the risk of frost during spring bloom, but the increased weather variability, warmer winters, more frequent and intense weather extremes, and a lengthening growing season have created unique new challenges for Steve Ela, the fourth-generation owner and operator of Ela Family Farms.

Ela Family Farms is located on the Western Slope of the Rockies in a region known for having the best conditions for fruit production in Colorado: 300 days of sunshine, low humidity, ample high-quality water, warm days and cool nights, and a relatively long frost-free period. Steve uses certified organic practices to manage 85 acres planted in 23 varieties of apples and 29 varieties of pears, peaches, cherries, plums, and tomatoes. The farm employs four full-time workers and up to 18 people during the height of the growing season. Virtually all of the fruit produced on the farm is distributed in Colorado through direct markets as fresh fruit or value-added products such as applesauce, fruit butters, jams, and cider. Farm products are sold through the internet and a CSA, at farmers' markets all along Colorado's Front Range, and to specialty food stores and gourmet restaurants throughout the state.

Since about 2000, Steve has been challenged by increased production losses associated with more variable spring weather. According to Steve, over the time his family has managed the farm, frost could be expected to cause significant yield losses about 1 year in 10; however, since about 2000, the risk of significant frost damage has increased so rapidly that it now occurs every year. "It used to be that growers didn't need wind machines and other frost protection and they got through just fine," says Steve, "but now we have the whole place covered in wind machines." Still, Ela Family Farms has remained a successful business in a region where fruit farms have declined by 75 % over the last 20 years. Steve believes that his decision to move into high-value direct markets has been a major factor in the resilience of Ela Family Farms to changing social and climatic conditions.

Although the lengthening growing season has improved growing conditions for some apple varieties on the farm, warmer winters, more variable spring weather, reduced snowpack, and more extreme weather have increased production risks, particularly in the last decade. Earlier springs and more variable temperatures in the spring increase the risk of total crop loss from frost during spring flowering. This change in seasonal weather also adds a lot of uncertainty in orchard management, because fruit trees are thinned in the fall to reduce the number of fruits and to evenly space the fruits on a tree to increase fruit size and quality. The final crop load—the quantity of fruit remaining on the tree to maturity—determines the season's yield potential. More variable springs make it very difficult to manage crop load through fall thinning because losses from frost during spring flowering are no longer predictable.

Steve has employed primarily natural and technological resources to adapt to changing weather patterns. The farm's position on a hill about three quarters of a mile long with swales creates temperature differences across the farm landscape. Steve has stopped planting trees in some of the cooler swales because of increased risks of frost injury and locates new plantings on the higher, warmer parts of the landscape. He has also added propane burners and more wind machines for additional protection from late season frost. When the snowpack—the source of water supplies in his region—began to decline about a decade ago, Steve leased a neighboring farm to obtain additional water rights as insurance against drought.

Steve believes that the practice offering the most climate resilience to his production system is his use of diversified direct marketing. The high returns possible with direct markets have buffered the costs associated with increased production risks over the last decade and supported the accumulation of financial resources needed for effective adaptation. Direct marketing also cultivates the biodiversity needed to promote climate resilience because Steve can select varieties that are frost-hardy but do not ship well and so are not suitable for wholesale markets. In addition, the willingness of direct market customers to try new fruits and new varieties of familiar fruits gives Steve additional flexibility to select new cultivars as climate conditions change. Steve suggests that the uniform product requirements of industrial commodity markets increase climate risks to fruit production because growers are not free to select varieties that are best adapted to their local climate conditions.

Ela Family Farms offers an example of the climate resilience benefits of biodiversity and diversified direct marketing—as complementary agroecosystem qualities—and the resilience benefits of a high level of financial and technological assets. Steve is hopeful but concerned about the nature of the climate risks facing the farm. He feels confident that he has access to some of the best tools and information available to fruit growers, but he is not sure that means he can successfully manage the increasing variability if current trends continue to intensify in the future.

Soil quality and dynamic crop rotation enhance resilience to more variable and extreme weather in North Dakota

Gabe Brown has produced grain and livestock near Bismarck, North Dakota, for more than 30 years. Located in the Northern Great Plains, a region accustomed to extremes of heat and cold, severe storms, drought, and flood-producing rainfall, North Dakota has experienced the most rapid increase in average temperature in the continental USA over the last decade (Shafer et al. 2014). Gabe really noticed more frequent weather extremes starting around 2006 or 2007 as more variable weather began to complicate fieldwork.

When Gabe took over management of the ranch in 1991, the natural resource quality of the agroecosystem was low. Soils were degraded by years of intensive tillage, soil organic matter levels were very low, and light rains of as little as 0.5 in/h caused surface runoff which further degraded soils on the ranch. Weeds, insects, low soil moisture, and poor fertility all seemed to be holding down crop productivity. Gabe believed that the poor soil quality on the ranch was a key factor in these production challenges and began transitioning to no-till, diversified crop rotations, and management-intensive grazing to restore soil quality. Today, the soils on the ranch can absorb rainfalls of up to 8 in/h, and Gabe says that high soil quality is the best insurance he can get against the increasing weather variability and extremes bringing new stresses to North Dakota agriculture.

The Brown Ranch produces grains and livestock on about 2000 acres of native rangeland that has never been tilled, 1000 acres of perennial forage crops, and 2000 acres of unirrigated no-till cropland managed in a dynamic crop rotation that includes corn, peas (grain and forage types), spring wheat, oats, barley, sunflowers, vetch, triticale, rye, alfalfa, and a great diversity of cover crops. Dynamic crop rotations are designed to include several crop choices with different environmental requirements in each phase of the rotation, so the producer can fine-tune the crop rotation to best fit seasonal weather and soil conditions (Merrill et al. 2007). Producers managing dynamic crop rotations can also shift the percentage of cropland in fall versus spring-seeded crops to respond to changing seasonal precipitation patterns.

Dynamic crop rotations typically include the use of cover crops—actively managed plant species that are not marketed, but instead contribute to farm profitability indirectly by providing other important benefits to the agroecosystem. Cover crops are commonly used by sustainable producers to supply crop nutrients; suppress weeds, insects, or diseases; prevent soil erosion; build soil quality; prevent the loss of soil nutrients; and provide forages (Sustainable Agriculture Network 2007). The addition of cover crops to grain production systems has been shown to restore the health of soils that have been degraded by years of industrial agricultural practices (USDA-NRCS 2013). Cover crops are also being used to address the growing problem of herbicide-resistant weeds in no-till industrial farming systems (Unglesbee 2014).

Gabe has been an innovator of cover crop "cocktails," which are extremely diverse mixtures of cover crops grown in a polyculture of five or more species (McGuire 2013). The specific mix of species varies with farm system, planting season, and objective, but the aim is to maximize the capacity of the cover crop to flourish regardless of weather or soil conditions. High species diversity in the cocktail is the key to success, so cover crop cocktail mixes typically include at least one species from each of these five crop types: warm- and cool-season grasses, warm- and cool-season broadleaf species, and legumes.

Throughout the year at Brown's Ranch, Gabe plants as many as 70 different species and actively manages many more, including the diversity of plants in the restored grasslands. He also integrates cattle, sheep, and poultry into the ranch's crop rotation and grasslands. No insecticides or fungicides have been used on Brown's ranch for over a decade, herbicide use has been cut by over 75 %, and no synthetic fertilizer has been used since 2008. Corn yields average 20 % higher than the county average. Gabe says the short-term droughts and heat waves that are becoming increasingly common in his region have little or no impact on crop or livestock productivity on his ranch.

The biodiversity at Brown's Ranch appears to promote nutrient cycling, water conservation, and pest suppression over a wide range of environmental conditions. High soil quality captures and stores water for crop use between rainfalls and eliminates the need for supplemental irrigation. On-farm production and cycling of crop nutrients through cover crops and the integration of livestock create many weak connections that provide crop nutrient needs. The temporal and spatial biodiversity create a pest-suppressive landscape. These nutrient and pest management strategies also serve to couple the farm to local natural capital and increase the farm's autonomy from global energy and nutrient flows. Gabe cultivates social capital and participates in shared and reflective learning by collaborating with federal and state researchers interested in investigating his farming system, hosting workshops and tours at the ranch, and speaking regularly at farming conferences throughout the country.

Planned grazing of restored native prairie enhances resilience to extreme drought in Texas

The 77 Ranch near Blooming Grove, Texas, sits at what could be considered ground zero for climate change impact in the continental USA. Historic drought in the southern Great Plains in 2011 and 2012 led to massive destocking of beef cattle on ranches throughout the region. Declining cattle herds drove closures of cattle-feeding and processing operations in the region and cost thousands of jobs, while rising beef prices set new records. Yet through it all, Gary and Sue Price, owners and operators of the 77 Ranch, were able to maintain production of their cowherd without the need for supplemental feed or water. What sets the 77 Ranch apart from other ranches in the region? Why is it so resilient to drought?

The Prices began assembling their ranch almost 40 years ago through the purchase of neighboring croplands and degraded rangelands. The productivity of a remnant native tall grass prairie on the ranch in drought made a big impression on Gary. Using planned grazing (an adaptive management practice) and technical and financial support from numerous public and private organizations, Gary began to restore native prairies throughout the ranch. He was convinced that healthy native prairies could form the basis for a resilient, productive, and profitable cattle production system. The historic drought of 2011 and 2012 seems to have proven him right.

Gary uses planned grazing to manage a 190-cow beef herd on the restored native grasslands that dominate the 2500-acre ranch, which also has 200 acres of cropland and about 90 acres of improved pastures. More than 40 acres of small stock ponds and small lakes provide water for livestock and waterfowl and generate extra income through the lease of fishing and hunting rights. The majority of the ranch's income comes from marketing cattle into value-added wholesale cattle markets through a source-verified program.

The key to the resilience of the 77 Ranch appears to be the high-quality natural resource base cultivated by many years of planned grazing—coupled with the drought resistance of native grasses. A high-quality natural resource base—soil, water, and biodiversity—produces the response capacity needed to sustain beef production over a wide range of weather conditions. Equally important, the 77 Ranch enjoys a high level of social and financial capital generated through Gary's participation in public and privately funded natural resource development programs and educational and research opportunities. Gary says that the extreme drought in 2011–2012 made it very clear just how important soil health is to the success of the 77 Ranch. He has made it a priority to learn everything that he can to "make the place like a sponge" in order to remain successful in the event that climate change intensifies through mid-century as projected.

Although these cases, and the others reported by Lengnick (2015a) feature exceptional sustainable farmers and ranchers, the practices that these producers employ to cultivate sustainability and resilience through a focus on soil quality, biodiversity, and diversified high-value direct markets are widely used on sustainable farms and ranches throughout the country (see, for example, Sustainable Agriculture, Research and Education Program 2005). The environmental and productivity benefits reported by these case study producers have been well documented through empirical research exploring sustainable agriculture practices; however, the reported economic, social, and community benefits of sustainable agriculture have received less attention by researchers (National Research Council 2010).

A self-organizing cooperative food system in the Twin Cities

Like Paul Muller and Steve Ela, many sustainable producers who practice diversified marketing engage in more than just the production sector of their local and regional food systems. Because Paul markets directly to wholesalers, retailers, and consumers in the greater San Francisco region, he takes on the packaging, distribution, and retailing functions of the food system. Steve Ela supplies wholesalers, retailers, and consumers in the Denver region and along the Front Range, but he also processes some of the fruit produced on his farm and so takes on the processing functions of the food system as well. Although the production sector is typically the food system sector most sensitive to climate change exposures, the rest of the supply chain can also experience climate change disturbances. And like the production sector, the vulnerability and resilience of the supply chain can also be assessed.

We turn now to two case studies of food supply chains in the Twin Cities of Minnesota and Ontario, Canada, to the general resilience of a food system from "farm gate to plate." We explore the resilience behaviors of a cooperative food network in the Twin Cities metropolitan area as an example of a mature self-organizing regional food system. The case from Ontario, Canada, provides an example of how government investment in regional marketing infrastructure designed to cultivate producer diversity enhances regional food system resilience.

Metropolitan Minneapolis–St. Paul, Minnesota, is home to a thriving, self-organizing cooperative food system built over the last 40 years (Stockinger and Gutknecht 2014). This interdependent, connected network of 15 consumer cooperatives operates 17 retail food stores serving about 140,000 consumers in the metro area of almost three million inhabitants. The network of neighborhood coop grocery stores makes a substantial contribution to the urban economy. Total retail sales through this system were $179 million in FY 2012, of which $54 million has been from the sale of regionally produced products. In the 20 years between 1992 and 2012, retail coop membership increased eightfold and provided the operating and investment capital necessary for retail operations. As membership in coop groceries continues to grow, their member-owners provide start-up capital necessary for new stores to emerge and for existing stores to increase their square footage. Most stores are operating profitably in most years, and net earnings are trending up at 2.8 % compared to an industry average of 1.7 %.

The newest grocery in the Twin Cities coop scene is the Friendship Store in the South Minneapolis Powderhorn neighborhood. The Seward coop developed this new store in collaboration with the Greater Friendship Baptist Church to serve the 15 % of its membership who lives within walking distance of the site. The Seward coop also chose this site as a way to provide healthy food to an underserved neighborhood and to engage and grow new coop members. A majority of the staff for the new store are from the neighborhood, so the Friendship Store is also acting as a neighborhood economic engine.

All of the participants in the system, whether they are member-owners, retailers, distributors, or farmers, play a part in building a strong cooperative economic structure. The retailers rely on investment and governance from the 91,000 coop member-owners who connect the businesses to the community. Owner-member participation on retail boards of directors is a unique feedback mechanism for communicating values by which the retail should operate. In this way, the cooperative business is strongly connected to the values and needs of the community it serves. Members elect the board of directors, and the board is responsible for optimizing community needs and business best practices. Coop member-owners value local, sustainable, healthy, and fairly traded food and household products, and the stores reflect that preference in the products offered, how stores are designed and stocked, and through human resource management policies and practice.

The coops have a legacy of long-standing business relationships with more than 300 farmers in the region who serve the stores and sell product through a cooperatively owned distribution center. Currently, farmers direct-deliver about 60 % of the stores' local product. The cooperatively owned distributor—coop partners warehouse (CPW)—moves about 20 % of the local product sold at the groceries in one of two ways. CPW purchases product like a traditional distributor but also provides space for farmer-directed distribution services. Smaller farmers who sell to coop stores aggregate their product for shipment on farm and then share direct-to-store delivery tasks.

The Twin Cities cluster of retail cooperatives, farmers, and the cooperative distribution center is closely aligned with similar coop clusters in smaller cities and towns in the Upper Midwest, which also have overlapping and unique relationships with sustainable farmers, food supply chain businesses, and the communities they serve. People in towns in the Upper Midwest, with the Twin Cities as the urban core, are creating and sustaining a viable regional supply chain built to scale with sustainable regional farms. One of the core principles that cooperatives share is "cooperation among cooperatives." This is an explicit statement of connectedness at the business level.

Grocery and distribution cooperatives are only part of the coop story for mid-scale supply chains. Farmer marketing cooperatives such as Organic Valley and Shepard's Grain have decades of experience building regional supply chains for sustainably produced food. Both offer successful models of self-organizing food supply chains serving regional markets.

Organic Valley is a network of organic dairy producers based in La Farge, Wisconsin, and was a partner in developing the Twin Cities consumer coop scene. As a marketing cooperative, the business provides supply chain services to its farmer-owners. Organic Valley staff support 1600 farmers in 34 states, who are organized regionally into 43 milk production pools that serve regional markets across the country (Center for Integrated Agricultural Systems 2013). Similarly, Shepherd's Grain pools the grain of 60 growers in the Pacific Northwest, arranges with a strategic partner to mill and pack it, and then sells the value-added products to markets in the Pacific Northwest region (Center for Integrated Agricultural Systems 2012).

Wholesale markets for regionally produced food are built on the success farmers have had in direct markets. Supermarkets see local and regional food offerings as a potential competitive advantage in a highly competitive market (Lyson et al. 2008). These robust and successful efforts are taking place in a market environment that is largely unsupportive of regional food initiatives. What would happen if the policy and market environment shifted to one that was neutral or even supportive of regional food systems? Our last case looks at an example of government support for regional food production.

A case of public vision for a strong regional food system in Canada

Fearing that competition from US food supply chains could hurt Canadian farmers and reduce national food self-sufficiency, Ontario's provincial government invested in the start-up of a private, nonprofit food distribution center outside of Toronto in 1954. Fees collected from users of the facility repaid the initial start-up loan and have funded operations, maintenance, and improvements over the last 50 years. This thriving distribution terminal is governed by a board that serves under the provincial Ministry of Agriculture, Food and Rural Affairs. The Ontario Food Terminal is now the third largest terminal market in North America by volume, after Los Angeles and New York City, averaging 5.5 million pounds of produce per day (Ontario Food Terminal 2015). The terminal serves over 5000 registered wholesale buyers located in seven provinces, from caterers and small restaurants to large grocery chains and institutional clients.

The Ontario terminal addresses a significant barrier to the development of regional food supply chains: matching the scale of supply to the scale of the market. Retail scale is set by the retailers, and food retailing is dominated by big box stores like WalMart, CostCo, and Target. Buyers want to limit transaction costs and so tend to do business with shippers (farmers and processors shipping to wholesale markets) that can reliably ship very large quantities to private distribution centers serving specific chains.

The Ontario distribution center is unique in that it serves a diversity of farm sizes—large, medium, and small-scale farmers—creating market access for farm products produced within a 200-mi radius of the terminal. Twenty-one larger warehouse tenants account for about 60 % of the sales, while about 400 "farmers' market" wholesale vendors account for the remaining 40 %. The terminal rents office space and central cold storage to vendors, and it rents office space to businesses and nonprofit organizations that serve vendors and buyers, such as a bank, two restaurants, and grower associations. About 40 people are directly employed at the terminal, which also supports an estimated 100,000 additional jobs through associated businesses. A potent economic engine for the region, it is estimated that for every dollar of terminal sales, about three dollars are returned to the Ontario economy.

The Ontario Food Terminal adds redundancy to the for-profit food supply chain by offering distribution center space for independent businesses. This then provides market opportunities for vendors, so they can do business with buyers who are not part of vertically integrated supply chains or are not maximizing efficiencies of scale. The distribution center is open to smaller wholesale farmers, giving them a place to sell seasonal product to independent grocers, restaurants, and caterers. The terminal is an excellent example of appropriate connectedness and local interdependence.

Significance of these cases

These farm and food system cases offer models of food production and regional food supply chains that exhibit many of the behaviors associated with resilient agroecosystems. A remarkable level of biodiversity in the production sector reduces the need for imported water, feed, fertilizer, and pest control materials, couples the agroecosystem to local natural capital, and enhances the quality of the natural resource base on the farm and in the surrounding community. All of the case study producers benefit from the high level of social self-organization cultivated by participation in building innovation networks enriched by reflective and shared learning, and they supply local and regional food supply chains that, in most cases, they helped to develop. These agroecosystems are globally autonomous, except for fossil-fuel use, and locally interdependent. All of the case study farms have provided long-time financial support to one or more families, as well as a number of full-time and seasonal employees, suggesting that they are reasonably profitable. Taken together, these ecological and social behaviors may explain their remarkable response and recovery capacity in the face of more variable weather and extreme weather events during the last decade.

Most of the case study producers do more than simply produce farm products. They are also active participants in local and regional supply chains, taking on many of the processing, distribution, and retail sales functions of the food system beyond the farm gate. Although research on the impacts of climate change on North American food supply chains at any scale is sparse, examination of two regional food supply cases—a cooperative retail network and a nonprofit distribution network—suggests that both exhibit many behaviors of social resilience and foster ecological resilience through cooperative marketing arrangements with farms in the region. These supply chains are self-organizing, cultivate diversity, and add redundancy to the national and global food systems. They are locally interdependent, build human capital, and are appropriately connected and accumulate social and financial capital at both local and regional levels in the food system.

While these cases highlight particularly successful examples of sustainable producers and alternative regional supply chains, they are not unique. They are part of a growing movement to resolarize and reregionalize the American food system, offering a glimpse of a more sustainable and climate-resilient US food future.

Regional food system planning projects

Regional food economies are emerging globally and provide insight into how regionalization promotes resilience in human systems. People are organizing from multicounty to multistate scales to address food system issues, including transparency and fairness concerns between urban and rural interests. These efforts address long-term, structural changes intended to strengthen the food system, so food supply chains can weather disruptions. Some noteworthy regional food system planning projects incorporating resilience objectives include those based in Iowa, Vermont, New York, and New England.

The Iowa Food Systems Council engaged food system stakeholders across the state to develop a comprehensive approach for assessing food system resilience (Tagtow and Roberts 2011). Using 14 resilience indicators representing economics, environment, food and farm equity, and food access and health, this innovative food resilience assessment found that the health of Iowa's food system was poor. Among the recommendations for policy, program, and research strategies to improve sustainability and resilience of Iowa's food system were many focused on developing local and regional food system infrastructure, such as the establishment of regional food system councils to improve communication and coordination about food system issues among county agencies, institutions, and municipalities and a redirection of state economic development funds to support new small and mid-sized food production and processing businesses and regional food hubs.

Vermont's Center for Agricultural Economy developed a comprehensive strategic plan designed to enhance economic development in the Northeast Kingdom region of the state through the growth of local food systems (Campbell 2011). The planning process was based on a soil-to-soil, closed-loop food system model consistent with the goals of Vermont's Farm to Plate Investment Program. The plan presents a practical and credible path to achieve broad sustainability and resilience outcomes for the Northeast Kingdom food system and includes 60 indicators for assessing progress toward food system resilience goals, including local provision of production inputs and recycling of farm and food wastes; support for diversified and profitable local production; development of infrastructure sufficient to supply year-round consumer demand for some food items; food system processes that serve to enhance environmental quality; agriculture and food system skill development; and local provision of healthy, fresh, affordable local food for all residents.

The New York Regional Foodshed Project used geographic information system analysis to assess food production capacity, processing, and distribution infrastructure and access to healthy foods in the nine-state New York City metropolitan region (Conard et al. 2011). Using beef and apples as test cases, these researchers developed an optimization model to map production areas, identify gaps in processing infrastructure, and find efficient distribution configurations. This model may offer a powerful new tool for envisioning a more resilient US food system and identifying practical steps needed to realize that vision.

Food Solutions New England, a collaborative network that supports the work of the many organizations and individuals dedicated to food system change in New England, published *A New England Food Vision* in 2014 (Donahue et al. 2014). This report explored sustainable food production in the region, including natural resource concerns relevant to energy and water resources, climate change and biodiversity, and social concerns such as building food system capacity. Through widespread changes in the existing regional food system, including an expansion of farmland, these researchers project that New England could supply about 50 % of its food needs by 2060 while setting aside adequate room for smart growth and green development and keeping 70 % of the region in forests. This work recognized that a substantial volume of food trade with other regions located in the USA and abroad would be necessary to obtain the quantity and diversity of foods required to meet the dietary requirements of New England's population. A companion report analyzes policy barriers and gaps associated with the Vision's goal of increasing production and consumption of New England-sourced food and identifies the policy changes to support expanding production, strengthening food supply chains, and enhancing multistate cooperation toward a more robust and resilient regional food system (Bowell et al. 2014).

Ruhf (2015) shares the story of developing the New England Food Vision in the first issue of the Symposium on American Food Resilience. She suggests that the collaboration was facilitated by the "soft working borders," of the New England states, a legacy of the trust and cooperation cultivated by decades of institutional collaboration. The region's physical and cultural geography also shapes the potential for a self-reliant food economy. Ruhf views the urban to rural balance, a lack of dependence on federal farm programs and global trade, and high production diversity as important elements that have contributed to the region's food self-reliance. Although many of these characteristics likely enhance the resilience of the New England food system, Ruhf notes that resilience has not been an expressed goal of regional food efforts. Instead, food systems are viewed as a potential framework for achieving environmental, economic, and social goals that ultimately promote regional resilience.

A nationally integrated system of metropolitan foodsheds

In 2009, researchers working in the Collaborative Initiatives program at the Massachusetts Institute of Technology proposed a system of nationally integrated regional foodsheds as a solution to the public health harms of US industrial food and further developed the concept in a follow-up project (Collaborative Initiatives 2009 and 2011). These researchers identified the current structure of the US food system—the way food is produced, processed, and distributed—as a primary culprit in America's obesity epidemic and high rates of chronic disease. They identified foodshed reform as a critical factor in developing integrated solutions to national challenges in public health, environmental quality, energy use, and economics.

Modeled on the watershed concept, the concept of the foodshed offers a way to visualize the geographic area through which food flows from producers through the food system to consuming communities. The foodshed concept has proven to be a useful and popular framework for exploring food system sustainability (Peters et al. 2009). The Collaborative Initiatives researchers identified several changes critical to foodshed reform: a transition to more diversified production systems, the development of a regionally based processing and distribution infrastructure, and new models of food retail. Ironically, these recommendations echo those of New York City planners concerned about the impact of industrialization on the city's food self-reliance at the turn of the twentieth century (Hedden 1929).

The Collaborative Initiatives researchers suggested that a nationally integrated system of regional foodsheds offered a unique opportunity to build on the many local and regional foodshed projects already underway in the USA. Most of these projects are focused on feeding metropolitan regions (an area with a concentrated population of 50,000 or more), a topic of increasing interest as urban populations expand and climate change disturbances intensify (Jennings et al. 2015). Planners in the USA have already begun to develop plans for eight to ten US megaregions, which are connected networks of metropolitan areas projected to be home to more than 70 % of the US population by 2050 (Fig. 1). These emerging regions, linked by economic systems, transportation systems, history, culture, and natural resources, are viewed by planners as an important opportunity to reimagine twenty-first century housing and urban development, transportation systems, and farm policy (Regional Plan Association 2015). The integration of metropolitan foodsheds into megaregion planning offers a practical means for restructuring the US food system into a nationally integrated system of metropolitan foodsheds. Megaregions also offer a new focal scale of planning that incorporates both the local and regional scales into a national system.

Metropolitan areas present some unique benefits and challenges to the development of sustainable and resilient regional food systems. On the plus side, sustainable producers located in or near these areas have easy access to a large population of potential customers, high-value direct markets, and value-added processing opportunities (Hoppe and Banker 2010). Physical infrastructure for power, water, transportation, and other resources is usually well developed, and proximity to the metropolitan core offers opportunities for meaningful off-farm employment for nonfarming family members, as well as employment opportunities on farms and in the food system for the urban underemployed.

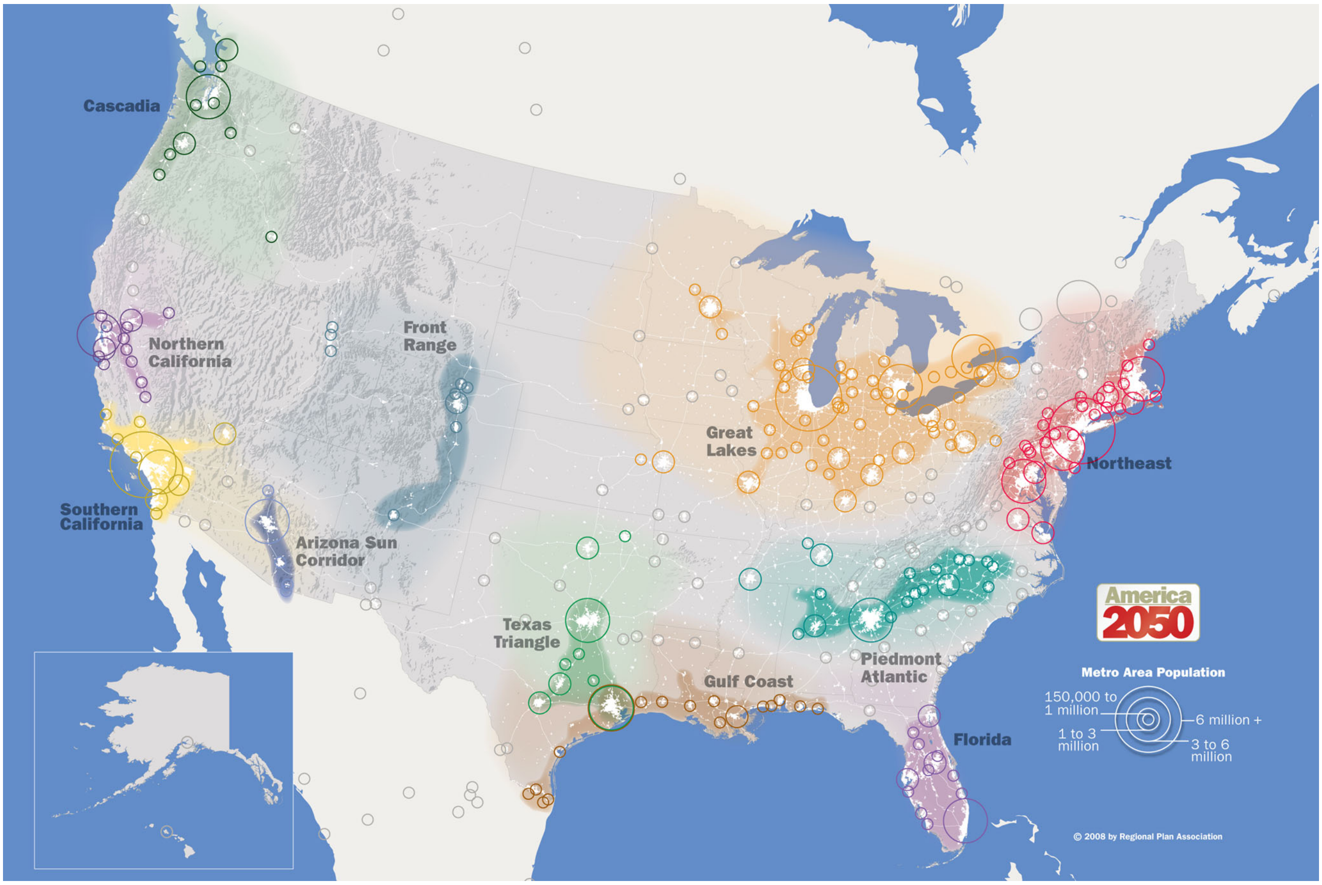

Fig. 1 Emerging US megaregions. During the second half of the twentieth century, metropolitan regions in the USA expanded to create large networks of metropolitan regions known as megaregions. Over the next 35 years, these 11 megaregions are expected to experience the most rapid population growth and economic expansion in the nation, stimulating new interest in coordinated planning and policy development at this scale (Regional Planning Association 2015)

Metropolitan areas and the periurban periphery also present some challenges to food production. Land values are high, non-farming residents may object to farming operations, and access to traditional farm services may be difficult (Hoppe and Banker 2010). Generally, urban supply chains are scaled for much larger wholesale volumes than can be supplied from farms within metro regions. Concentration in the grocery sector and a dearth of independent transportation partners are challenges for mid-scale farmers producing wholesale products for metro markets (Stevenson and Pirog 2008; Miller et al. 2015). Traffic congestion around cities creates a costly barrier to efficient freight delivery, and food is no exception. The existing relationships between businesses in food supply chains are predominantly national in scope, with few opportunities to develop regional connections (Day-Farnsworth and Miller 2014).

Competition for resources with municipal and industrial uses may also present considerable challenges, particularly as climate change intensifies, but close proximity of municipal, industrial, and agricultural systems will also encourage innovations that increase the efficiency of resource use through sharing and recycling (Hoppe and Banker 2010). Ultimately, addressing the power dynamic between urban and rural areas is a key to reversing the extractive behavior of cities and putting into place systemic solutions that cultivate sustainable and resilient urban regions (Jennings et al. 2015).

The "city region" is an emerging, landscape-based sustainable development concept well aligned with the concept of the metropolitan foodshed. City region development strategies redefine the relationship between urban and rural areas to recognize the potential for food systems to address shared challenges such as securing clean water supplies, conserving biodiversity, mitigating global warming, and cultivating climate resilience (Forster and Escudero 2014). A recent review of the relevant food system literature by Jennings et al. (2015) found solid empirical evidence that city region food systems promote regional economic development, catalyze innovation, and improve public health, but less evidence was found for the often assumed benefits to food security, nutrition, and environmental quality. These researchers found very few projects exploring the multiple benefits of city region food systems and recognized a need for comprehensive food system performance metrics to guide the planning and development of sustainable and resilient city region food systems.

Discussion

According to resilience theory, a restructuring of the US industrial food system to a nationally integrated network of sustainable metropolitan foodsheds offers the potential to enhance the climate resilience of the US food supply. A transition to diversified food systems would reduce food system dependence on imported energy and materials by increasing biological diversity at the farm and landscape scale and through the coupling of agroecosystems to local natural resources. Recent comprehensive reviews of empirical research confirm that diversified agricultural production systems can be as productive as industrial systems with substantially lower energy, water, fertilizer, and pesticide inputs while, at the same time, maintaining or enhancing ecosystem services crucial to farm and community sustainability and resilience (National Research Council 2010; Kremen and Miles 2012; Liebman and Schulte 2015).

The modularity created through a network of diversified metropolian food systems would likely reduce the vulnerability of our national food supply to damaging climate change effects in areas of concentrated production and processing, such as California's Central Valley or the southern Great Plains, and to climate change stresses and disturbances of national and global supply chains. The modular structure could stimulate innovation in food production, processing, and distribution as metropolitan foodsheds evolved into unique agroecosystems adapted to regional ecological and social conditions. Resilience theory suggests that the diversity and modularity of a national network of diversified metropolitan foodsheds would also enhance the regional accumulation of a balanced portfolio of capital assets needed to support the response, recovery, and transformation capacities required for a climate-resilient national food system. Incorporating metropolitan foodsheds into comprehensive megaregion development goals provides a potential path to enhanced sustainability and resilience of the US food system.

Although there is little empirical evidence for the climate resilience benefits of such a regional restructuring of the US food system, the evidence for the environmental benefits of more diversified agroecosystems is strong (Kremen and Miles 2012; Liebman and Schulte 2015). We could begin now to build on the existing network of local and regional food systems, while questions about the climate resilience benefits of modularity and the regional scale are addressed through further research.

In a recent review of the barriers and opportunities for enhancing the diversification of agricultural production in industrialized countries, Iles and Marsh (2012) recognized the need for broad support for producers transitioning to more diversified production systems. They recommend shifting existing public support for agriculture from policies and programs that favor industrial producers to those favoring producers who already manage or wish to transition to diversified systems. Some specific recommendations include: increased public support for the development of new knowledge, materials, and training programs needed by producers managing diversified production systems; the recruitment and retention of new sustainable farmers; incentives for agricultural resource conservation; and regional economic development that supports diversified production.

These recommendations echo many earlier calls by the sustainable food movement for reform of the US industrial food system over the last 40 years. Over that time, evidence for the multitude of environmental, social, and economic harms of industrial food has continued to mount as our understanding of food system sustainability and resilience has grown. We have the knowledge and the financial resources required to begin the restoration of the natural, human, and social assets needed to achieve the transition to a more climate-resilient food future.

Conclusions

Despite its remarkable performance over the last century, the US industrial food system may not be resilient to unprecedented twenty-first century challenges: climate change; declining quality and quantity of natural resources; highly specialized and concentrated production, supply, and marketing chains; reliance on external or distant resources; and government subsidies that mask these vulnerabilities. The existing food system does not exhibit the behaviors characteristic of a resilient agroecosystem. More than 30 years of sustainable food system research and practice suggest that a transformation—a change in form, function, and purpose—is needed to cultivate the response, recovery, and transformation capacity required for a climate-resilient US food system.

A nationally integrated system of metropolitan foodsheds has been proposed as a model that appears to promote broad sustainability and climate resilience goals and is well aligned with the city region as a newly emerging sustainable development concept, but many questions remain. Empirical evidence for the environmental benefits of diversified agricultural production systems is strong, but evidence for social and economic benefits is less clear. Empirical support for the economic development, innovation, and public health benefits of city region food systems is strong, but there is less evidence for benefits to food security, nutrition, and environmental quality. Very few comprehensive projects exploring the sustainability benefits of regional food systems have been reported, and climate resilience has only very recently become a focus of food system research and planning efforts. We can begin now to shift public support to producers who currently manage or wish to transition to diversified production systems and to fund the development of regional food system infrastructure.

More research, coupled with action, is needed to confirm the climate resilience benefits of sustainable regional food systems, refine resilience indicators, and develop food system performance metrics to guide a transformation of the US food system to a more sustainable and resilient future.

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