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California's drought as opportunity: Redesigning U.S. agriculture for a changing climate

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Abstract

The impacts of climate change are already affecting the production and profitability of agricultural systems, and these trends are expected to continue in the future. Without support from ecosystem functions, an agricultural system designed exclusively to maximize short-term production is vulnerable to extreme weather events such as droughts and floods. This results in high costs for farmers and ultimately for society at large, in economic and ecological terms. Complex agroecosystems that maximize biological interactions and conserve soil are better protected from extreme events, and thus are overall more resilient to climate change. This paper reviews the evidence demonstrating greater resilience on farms that maximize diversity, build soil organic matter, and incorporate other agroecological or 'sustainable' practices. We then discuss the current water crisis in California in the context of the vulnerability of our current agricultural systems to climate change, highlighting this as an opportunity to redirect agricultural policies and economic incentives. The projected increase in the frequency and intensity of climate extremes calls for policies that are concerned not only with present crises, but that also encourage a new culture of forward-thinking practices around land and water use. We highlight France's new Law for the Future of Agriculture, Food and Forestry as an example of national policy supporting agroecology. Applying an agroecological approach to increase resilience will enable the U.S. to tackle the twin challenges of food production and increasing climatic unpredictability.

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Introduction

Climate change is affecting the production and profitability of agricultural systems, and this is expected to continue in the future. Projections show increased temperatures, changes in precipitation cycles, greater frequency of extreme weather events such as hurricanes and droughts, decreased topsoil moisture, and shifting pest populations (Vergara et al., 2014). In California, USA, the sustained drought of 2011–2016 has demonstrated one such effect of climate change that is expected to be more common. Drought cost California's agricultural industry $1.5 billion in 2014, based on losses in crop revenue, livestock value, and the cost of groundwater pumping (Howitt et al., 2014). Economic loss in California's agricultural sector is likely to continue based on projected climate and continued water shortages.

How can these agricultural losses and costs be minimized? What examples exist of agricultural systems that withstand drought, increased temperatures, flooding, and pest pressure? What is needed to replicate these resilient farm systems, in terms of agricultural policy, economic incentives, and cultural acceptance? We argue that this moment represents an opportunity to shift the existing agricultural paradigm in the United States to plan for long-term functionality in a changing climate. Hence, California's drought can be seen as an opportunity in that it forces consumers, farmers, and policymakers to recognize the limits to natural resource use and to transform the current U.S. agricultural policy framework. Willingness to enact necessary policy changes to avoid a food and water crisis will require public pressure and support, farmer engagement, and collaboration across different levels of governance (local, state, national) and across different sectors of government (agriculture, water, natural resources).

Focusing on water restrictions as the primary means to arrive at a target level of water use is an incomplete approach to natural resource management, one which is distracting from a more fruitful conversation about truly *sustainable* agriculture. Setting water use limitations based on actual recharge rates is an approach that focuses on reaching a target, but the other critical piece is to address the questions: (1) How will agriculture achieve the goal of limiting water use without compromising food production? and (2) How can farmers and land users build resilience in their system to prepare for the future? An essential move is to redesign the agricultural systems that are built upon unsustainable practices, which will require forward-thinking policies that reflect a commitment to this paradigm shift.

Below, we review examples of resilient agroecosystems around the world, many documented within the field of agroecology. We then highlight an example of agroecology applied at a national scale due to policies and support from the French government. We propose that governmental support is needed in the U.S. to help California's agricultural sector withstand and adapt to future water shortages, and to incentivize and promote the widespread adoption of sustainable agriculture.

Agroecology and agroecosystem resilience

Agroecology is "the application of ecological concepts and principles to the design and management of sustainable agroecosystems" (Gliessman, 1998), including maximizing nutrient cycling, minimizing external inputs, and conserving soil, water and energy. Agroecology is an approach that integrates ecological science with other scientific disciplines and knowledge systems (e.g. local, indigenous) to guide research and actions towards the sustainable transformation of our current agrifood system (Méndez et al., 2013).

Complex and diverse agricultural systems are less vulnerable to extreme weather events such as droughts and floods, and thus are overall more resilient to climate change (IPES, 2016). Many agroecological practices help build stable soils, which in turn are better able to maintain soil moisture during droughts and are less susceptible to erosion from storms and flooding (Magdoff and Van Es, 2000). Soils with high levels of organic matter have higher water-retention capacity, which maximizes the water available to plants during and following rainfall events (Hudson, 1994; Altieri et al., 2015). Soil organic matter can be maintained with crop residue application, cover cropping, and reduced tillage, leading to crop yield improvements and drought resistance (Lal, 2009). The evidence that agroecological practices build climate resilience has been analyzed for coffee farms in the tropics, which are highly vulnerable to climate extremes (Morris et al., in review), and has shown that shaded coffee agroforestry systems increase microclimate control, retain soil moisture, minimize erosion, increase nutrient use efficiency, maximize yields, and provide pest and disease control. In Brazil, incorporation of crop residues on coffee farms increased soil organic matter and soil water retention capacity, reduced soil temperature, and allowed better root system distribution (Camargo et al., 2010). In Costa Rica, coffee intercropped with leguminous trees (*Inga densiflora*) had higher water infiltration rates and less water runoff than coffee monocultures (Cannavo et al., 2011), while in Uganda, coffee agroforestry plots had 2.6 t C/ha more soil organic Carbon and significantly higher bulk density than coffee monocultures (Tumwebaze and Byakagaba, 2016).

Agroecology for resilience

Resilience refers to a system's capacity to rebound after absorbing a disturbance (Cutter et al., 2008). Resilience can be viewed as an outcome, in which a system or population is able to cope with a hazard, or a process in which learning is continually applied to improve decisions and capacity. Coping capacity is the ability to respond to an occurrence of harm and to avoid or minimize negative effects (Saldaña-Zorrilla, 2008). Coping strategies may provide immediate relief but are not long-term adaptation strategies. Adaptive capacity is the ability to gradually transform in order to adjust to change. A key element of increasing the adaptive capacity of farms is building agroecosystem resilience to withstand climate extremes, such as drought and floods, and to maintain or recover their productive capacity with limited losses and costs. Many farmers around the world cope with and prepare for climate change by incorporating agrobiodiversity and soil conservation practices. They minimize crop loss through increased use of drought tolerant local varieties, water harvesting, mixed cropping, agroforestry, and soil conservation practices (Altieri and Toledo, 2011). Agricultural biodiversity helps cushion farms from shocks such as extreme weather events (Jarvis et al., 2007). Incorporating spatial and temporal diversity on farms can enhance beneficial biotic interactions and support a suite of ecosystem services beyond simple short-term production (Kremen et al., 2012; Mijatović et al., 2013). These ecosystem services, including erosion control, microclimate control (Laderach et al., 2010), pollination (Ricketts, 2004), and pest control (Scherr and McNeely, 2008) serve to support and sustain the healthy functioning of agroecosystems (Tilman et al. 2002).

Observations of agricultural resilience in the last several decades reveal that farms with healthier soils and higher agricultural biodiversity are better able to rebound after extreme climatic events. Cover cropping, the application of compost or manure, no till, agroforestry, fallow periods, and riparian buffers accumulate soil organic matter, increase soil water-holding capacity, and thus increase drought resistance for crops (Kremen and Miles, 2012). A 21-year study in Switzerland showed 20–40% higher water-holding capacity in organically-managed soils than conventionally-managed soils (Maeder et al., 2002). A 31-year field trial in Ontario demonstrated that increasing the complexity of crop rotations and minimizing tillage resulted in more consistent yields in periods of extreme weather conditions (Gaudin et al., 2015). A study conducted in Central American hillsides after Hurricane Mitch showed that farmers who used agroecological practices such as cover cropping, intercropping and agroforestry had 40% more topsoil on average and experienced 49% lower incidence of landslides than their conventional monoculture neighbors (Holt-Gimenez, 2002). In Chiapas, Mexico, more vegetatively complex coffee farms suffered less landslide damage from Hurricane Stan than simplified systems (Philpott et al., 2008). Diversification of a corn-soybean rotation to include perennial crops in the U.S. Corn Belt resulted in soil and water conservation and soil nutrient retention, as well as a reduction in agrochemical use without effects on yield or profitability (Liebman et al., 2013). These examples demonstrate the potential for agroecological practices to increase farm resilience.

Yields and productivity

In addition, contrary to the long-held assumption that organic or agroecological farms are less productive than large-scale conventional farms, diverse agroecosystems can produce higher yields per unit of land than monocultures. Research has shown that organic agriculture produces yields sufficient to 'feed the world' at present and for a growing population, without the need for agricultural expansion (Badgley et al., 2007). Various trials and meta-analyses have concluded that yields are comparable for organic and conventional fields (Ponisio et al., 2015, Pimentel et al., 2005), while others have shown a great deal of variability in yields depending on the crop, climatic and geographic conditions, and specific management practices (DePonti et al., 2012; Seufert et al., 2012). Productivity in terms of harvestable products per unit area is higher in polycultures than monocultures with the same level of management (Altieri, 1999). Yield advantages can range from 20–60% depending on crops, climate, and management factors. These yield advantages are attributable to more efficient use of water, light, and nutrients in polycultures and the maximization of vertical space of different crops (Altieri and Toledo, 2011).

Many of the principles of agroecology and other sustainable agriculture approaches can be applied to different geographies and crop or livestock systems to improve yields without reliance on agrochemicals and irrigation. For example, in Mexico one hectare planted with a mixture of maize, squash and beans can produce as much as 1.73 ha of a maize monoculture. In Brazil, intercropped maize and beans exhibited a yield advantage of 28 percent over maize monocultures. In the Brazilian Amazon, Kayapo yields are 200% higher in agroecological systems than they are in systems that use agrochemicals (Altieri and Toledo, 2011). In the United States, the Rodale Institute long-term trial of corn and soybeans managed conventionally versus organically showed that organic crops (fertilized with manure and intercropped with legumes) had significantly higher yields than conventional in 4 out of 5 of the drought years between 1988 and 1999 (Lotter et al., 2003). Manure and legume treatments improved soil water-holding capacity, water infiltration rate, and water capture efficiency, leading to higher yields in periods of water-stress (Lotter et al., 2003). A long-term, large scale trial in Iowa demonstrated that cropping system diversification of maize and soybean resulted in lower costs from reduced chemical inputs and higher yields over time (Davis et al., 2012). These examples from throughout Latin America and the United States challenge the assumption that diversified and organically managed farms are less productive than conventionally managed farms.

In the following section, we discuss the current prolonged drought in California as an example of climate stress, and the potential for widespread adoption of agroecological practices to help cushion farms from such challenges.

Drought as opportunity? The case of California

We have arrived at our current industrial agriculture model based on the maximization of short-term yields and the argument of 'efficiency'- the premise that the larger and more uniform the farm, the cheaper it is to produce each unit of output. This assumption has justified the funding of large-scale monocultures rather than small-scale, decentralized, diversified farming. California's current agricultural systems are unsustainable by design, given their reliance on irrigation in an arid climate, as are many farms throughout the U.S. Monocultures of fruits, nut trees, and alfalfa for animal feed occupy the desert of California's Central Valley, and those require irrigation at levels that cannot be sustained. Three-quarters of California's cropland is irrigated, mainly concentrated in the Central Valley which encompasses the Sacramento Valley and San Joaquin Valley (See Figure 1) (California Department of Conservation, 2010; Mount et al., 2014; The United States Department of Agriculture - USDA, 2015). By some estimates, California only has enough freshwater stored to meet current levels of use for 1–2 years (Famiglietti, 2014). Various aspects of California's agriculture have recently been criticized by the media and public, including the high water requirements of some crops such

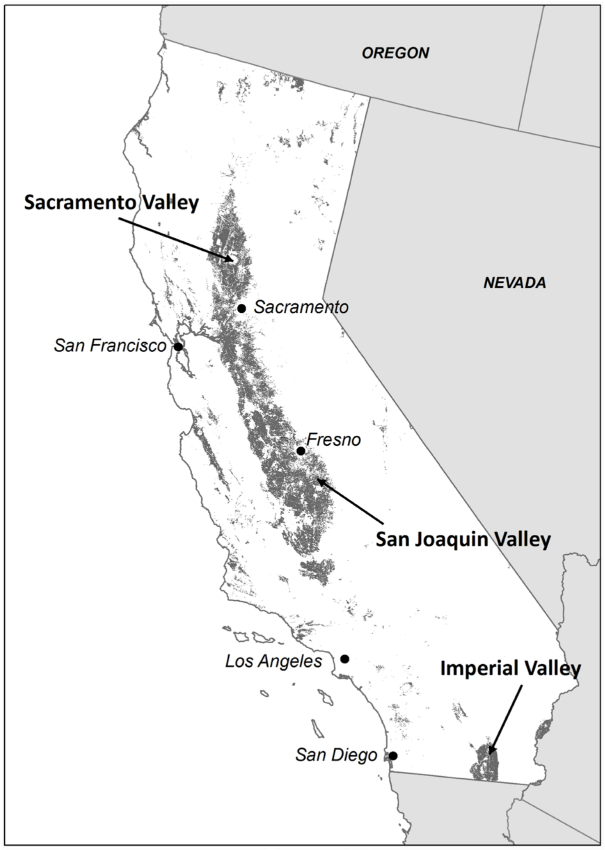

Figure 1

California's irrigated cropland, 2012.

The shaded area shows California's irrigated agriculture, which represents 75% of all agriculture in the state. Data sources: USGS, 2015; Natural Earth, 2015.

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as almonds (Holthaus, 2014). In addition, California exports alfalfa hay to Asia and the Middle East to feed livestock, which is indirectly 'exporting' one hundred million gallons of California's water rather than being used to nourish domestic crops and people (Leithead, 2014).

California's agriculture has recently suffered from drought and resulting freshwater shortages beginning in 2011. The drought has exposed the vulnerability of the region's agricultural systems, which points to the need to implement more sustainable practices for this and other extreme conditions. While drought is a characteristic feature of the climate in California, this current drought is among the most severe in the last millennium for its accumulated moisture deficit (Griffin and Anchukaitis, 2014). Paleoclimatic records show that multi-annual droughts have been common in southern California since 800 A.D., especially in the medieval period (800–1300) which was characterized by warm temperatures (MacDonald, 2007). In the last century, the Dust Bowl of the 1930s in the western United States was characterized by a prolonged decadal-scale drought which, coupled with unsustainable agricultural practices (heavy tillage, monocultures of annual grain crops), resulted in crisis (Eckholm, 1976). More recently, prolonged droughts afflicted California in the late 1970s and again in the early 1980s; however, one notable difference is that California's population today is roughly double that of the 1970s (Dimick, 2015).

The combination of sustained low precipitation and high temperatures is the driving force of prolonged droughts. While records show that similar low precipitation levels have occurred in the past 1200 years, the unprecedented high temperatures of these recent years could be a determinant of the particularly high drought severity (Griffin and Anchukaitis, 2014). While precipitation sets the occurrence and duration of droughts, high temperatures can exacerbate their severity as a consequence of increased evaporative demand. For southern California, projections of future temperature from general circulation models show that climate change will lead to higher temperatures, especially during summer months (MacDonald, 2010; Pierce et al., 2013).

In recent years, the absence of sufficient water supply from precipitation, coupled with decreased snowmelt from the Sierra Nevada and Cascade mountain ranges, has led to significant surface water shortages (Dimick, 2015; Hayden, 2015; Venton, 2015). Four hundred thousand acres of California farmland were taken out of production in 2014 due to a combination of the drought and difficulty accessing irrigation water (American Farmland Trust, 2015). But given that 32–40% of California's irrigated cropland is planted to high-value perennials including nuts, grapes and other fruits, these crops must be watered even in drought years (Mount et al., 2014). Farmers have compensated for the freshwater shortages by drawing more heavily on groundwater resources, with a 62% increase in groundwater pumping in 2014. Since aquifers are not being recharged as rapidly as they are being depleted, farmers are digging deeper wells to reach stored groundwater. The results are increasingly high costs of pumping, salt intrusions into aquifers, and land subsidence. Parts of the San Joaquin valley are undergoing faster rates of land subsidence than ever, which results in costly infrastructure damage and reduced flow capacity of canals. Overdrawing groundwater also causes compaction, which permanently decreases capacity for future groundwater storage; this occurred in the Central Valley in the 1960s and 70s and again over the past several years (Sneed et al., 2013).

California's Governor Brown has been criticized for responding to the current drought with water restrictions for residential and commercial water users, while sparing much of agriculture. Irrigated agriculture accounts for 74% of all freshwater withdrawals in the state (USGS, 2010). On the other hand, farming trade groups such as California Agricultural Council contend that agriculture has already made improvements in terms of water efficiency, and that agricultural water restrictions would unduly harm the agricultural sector and the state's economy. Direct agricultural production represents 2% of California's economy (3–4% when multiplier effects are included) (Paggi, 2011). In addition to the state economy as a whole, farmers' livelihoods are threatened by water shortages, and given that one-third of U.S. vegetables and two-thirds of U.S. fruit and nuts are grown in California, the public's food supply and the cost of food are also affected (USDA, 2015).

Water efficiency and agricultural technology vs. systems thinking and design

Opportunities exist to improve agricultural water efficiency and other technological solutions to respond to drought. Climatic surveillance and early warning systems can help farmers minimize water waste and properly time irrigation for climate adaptation (Vergara et al, 2014). Drones using thermal cameras can detect leaks in irrigation lines from coyote chewing damage, and can determine if crops are water-stressed or overwatered. Desalination has also been considered a potential solution to water shortage. However, these technologies are expensive, short-term responses that do not address the root causes of unsustainable agricultural production. Since the Green Revolution, high-tech approaches to agricultural challenges have diverted attention and resources away from broader efforts to promote sustainable practices and build resilient agroecosystems. Technology has a role to play in maximizing the efficiency of resource use. However, an exclusive focus on technological solutions suggests that agricultural systems and their environs can be completely controlled, when in reality there are complex interactions among plants, other organisms and climatic variables. Crops do not exist in isolation from soils, the surrounding landscape, and the atmosphere. Similarly, crop insurance programs, while important in the short-term, do nothing to ensure that farmers adapt their agricultural practices and farm design to increase resilience and ensure long-term sustainability.

Of all sectors- domestic, commercial, and agricultural- agriculture wastes the most water, both in the U.S. and worldwide. Stricter price controls, coupled with subsidies for conversion from wasteful flood irrigation to drip irrigation, would help encourage water conservation. Today, 39% of California's irrigated farmland, or nearly 3 million acres, uses efficient drip irrigation. Though this represents a substantial improvement over the past 3 decades, 3.5 million acres of California's farmland is still under flood irrigation (Fishman, 2015). With farmers continuing to dig deeper wells and overdraw groundwater reserves, implementation of the recently passed 'Sustainable Groundwater Management Act' (SGMA) is urgently needed. The SGMA will regulate 96% of the state's groundwater use and has potential to limit groundwater overdrawing. Unsurprisingly, the agricultural community has not embraced this law; all legislators of the San Joaquin Valley voted against it (Green et al., 2015). And the ambiguity of the law's wording will likely result in varying interpretations of what is 'sustainable' use vs. 'undesirable results' (Haroff and Kearns, 2015). While stricter water pricing and water use efficiency can be promoted as short-term adaptation strategies, they must be complemented with longer-term solutions to build resilience of the agroecosystem and the food system (Hanak and Lund, 2012).

Agroecology promotes a more participatory approach to agricultural programs and laws by empowering farmers and citizens, and incorporating their knowledge and perspective. Farmer organizations in the U.S. are diverse and many already support agroecology; for example, California's Community Alliance with Family Farmers (CAFF). It is a fundamental principle of agroecology to incorporate farmers' input in making change, for example by including farmers in advisory councils and giving farmers a voice in research design and project implementation. If this principle were to be applied in redesigning U.S. land, water, and agricultural policy, perhaps more farmer organizations would be amenable to changing their practices and even leading the way in the transition.

Is this the moment for an agroecological transition?

A widespread agroecological transition will need to overcome massive challenges, including the deeply entrenched corporate structure of the current food system. An additional complication is that a true paradigm shift necessitates change in public sector regulations, private individual actions, and collective consciousness (Adger, 2016), all of which take time and substantial coordinated effort. However, in the U.S. and other nations, grassroots movements for sustainable food systems continue to grow. At the global scale, key leaders in the international food and agriculture community have called for an agroecological transition and brought agroecology into the mainstream (IPES, 2016). The former UN Special Rapporteur on the right to food Olivier de Schutter recently called for a global paradigm shift toward sustainable agriculture (De Schutter, 2010). In 2009, the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), including 400 experts, the FAO, the World Bank and other international organizations, called for a fundamental paradigm shift in global agriculture, encouraging widespread adoption of agroecological practices (IAASTD, 2009). This leadership support for an agroecological transition seems to signal a shift in collective consciousness.

At the national level, momentum continues to build for sustainable food movements, including organic, agroecology, and local food. Consumer demand has driven significant increases in organic food sales, sending a message both to growers and policymakers that the public is concerned with how and where food is produced. From 2001–2011, U.S. acreage of organic fruit production nearly tripled (USDA ERS, 2013). The 2014 Farm Bill has increased funding to support organic agriculture (Greene, 2014). Government grants from USDA, Sustainable Agriculture Research & Education (SARE), University research, direct funding and Extension also represent opportunities to shift support toward sustainable agriculture practices. The Land Institute's proposed '50 Year Farm Bill' is one excellent example of a plan to approach agriculture through a long-term vision, including developing more resilient perennial grain crops.[1] The Union of Concerned Scientists' 'Healthy Farm Plan' also outlines specific steps to achieve more sustainable agriculture in the U.S. (UCS, 2013). A 2016 report by the International Panel of Experts on Sustainable Food Systems '*From Uniformity to Diversity: a paradigm shift from industrial agriculture to diversified agroecological systems*', explores the mounting evidence in favor of massive food and agriculture transformation (IPES-Food, 2016).

Innovative research and outreach on sustainable agriculture would spread and thrive if given the support from governmental programs, private investors, and philanthropic organizations that has been given to large-scale industrial agriculture. California is in a position to spark the next wave of sustainable agriculture, with its record of progressive environmental policies including one of the strongest renewable energy laws in the country and the strictest animal antibiotic laws of any state. This 'California effect' has played out with several environmental policies, in which California's legislation has paved the way for other states, the federal government, and corporations to adopt more stringent environmental standards. In the 1970s, California enacted more stringent auto emissions standards than the national standards, which served as a catalyst for the EPA to then adopt the same stricter legislation at the federal level (Klepetar, 2012). By preemptively enacting stricter environmental policies, California led the way to more stringent national emissions standards.

The recent drought, and the drought of 2012-2013 that afflicted much of the U.S. midwest and west, contribute to the momentum bringing California and the U.S. closer to agricultural transformation (Mallya et al., 2013). After the 2012 drought, many NGOs and scientists called for sustainable agriculture to be adopted, yet transition does not happen overnight, particularly when powerful actors have financial interest in maintaining the current system. The U.S. is undergoing similar movements for social and environmental change related to climate legislation, GMO labeling, gun control, and increasing the minimum wage (among others), and has historically experienced radical movements that unfolded over many years (e.g. Civil Rights, Women's Rights, same-sex marriage, Occupy Wall Street, among many others).

This paradigm shift is an ongoing process of agroecological transition, not a single moment of crisis necessitating a drastic and immediate response. In contrast, Cuba's 'Special Period' of food shortages in the early 1990s triggered rapid agroecological change out of necessity, which was facilitated by Cuba's top-down government structure[2]. The U.S. too has suffered agricultural crisis before, and the federal government responded relatively swiftly and effectively. We recall the Dust Bowl of the 1930s in the North American Great Plains, in which drought conditions coupled with unsustainable agricultural land management (e.g. tillage, continuous cropping, overgrazing) led to a regional ecological, economic, and health crisis (Heffernan, 2013; McLeman et al., 2014; Ritzel et al., 2013; USDA ERS, 2012). Enormous dust storms ripped up overplowed fields and overgrazed pastures. "Black blizzards" blew eastward from North and South Dakota, picking up an estimated 300 million tons of topsoil and choking people, shredding crops and killing livestock along the way (Baveye et al., 2011). The federal government responded by creating the Soil Conservation Service, and establishing projects to support rural agricultural economies and socio-economic welfare, and incentivize soil and land conservation with terracing, contour plowing, conservation tillage, and tree-planting for shelterbelts (Baveye et al., 2011; McLeman et al., 2014). Erosion control districts were delineated, zoning regulations were enacted, and farmers were incentivized to withdraw marginal lands from agriculture, both to allow land conservation and to stabilize markets.

Lessons can be drawn from the Dust Bowl and resulting government programs (Fraser, 2013). One similarity with today's situation is that unsustainable agricultural practices exacerbated the impact of prolonged drought. One difference is that today the capacity of the federal government to enact meaningful agricultural legislation is limited by the financial and political power of corporate interests. Corporate control of the food system includes multinational companies dominating seed markets, agrochemical markets, and food processing and retail, with the reach of food corporations extending into food and trade policy influence (Clapp and Fuchs, 2009). Other sources of power for agri-business include U.S. policy systems and subsidies directed towards commodity crop production, and Farm Bill programs focused on short-term goals rather than long-term economic, social, or environmental sustainability (Reganold et al., 2011). In our time, the power to transition toward a transformative agricultural system is in engaged grassroots movements. The ease of digital information access and sharing have the potential to complement scientific research with a groundswell of demand for legislative action. The U.S. Farm Bill and its conservation programs need to continue the work started during the Dust Bowl and help U.S. to overcome current challenges before they become catastrophic.

Supporting the agroecological transition

Rather than taking a near-sighted view of the problem of water scarcity, we must use this opportunity to revisit U.S. agricultural and water policies to reflect current realities. This will require a variety of interventions and forms of engagement, including tapping into grassroots environmental movements, engaging farmers in planning and policymaking, and phasing in progressive agricultural policies at the state and national levels. A major step would be the removal of subsidies and R&D funding for industrial agriculture and the redirection of financial incentives toward agroecological farms. The lion's share of U.S. agricultural funding supports the industrial agriculture model, and sustainable agricultural practices including organic have remained on the sidelines. Only 10% of USDA grants fund projects involving agroecology, and only 5% fund projects that are considered transformative agriculture (DeLonge et al., 2016). The largest portion of USDA's sustainable agriculture grants were allocated to improving efficiency of conventional agriculture (DeLonge et al., 2016), essentially supporting minor, incremental improvements within the current broken system. Crop insurance helps protect farmers against crop loss without requiring them to change their farming practices. Instead, crop insurance should be contingent on farmers demonstrating that their current practices build resilience of the farming system. Farm Bill subsidies and insurance must prioritize rewarding farmers for management practices that restore ecosystems and that can be sustained into the future without exceeding natural resource thresholds.

In addition to supporting sustainable production practices at the farm level, policies are needed to support a sustainable transition throughout the food system, including: 1. Financial support for agroecological research, 2. Extension education and opportunities for horizontal knowledge transfer including farmer-to-farmer exchanges, and 3. Cross-sectoral coordination to develop market opportunities and connect growers with markets. Examples of this type of support include the work of Appropriate Technology Transfer for Rural Areas (ATTRA) at the national level and the Ecological Farming Association within California, which provide educational resources on sustainable agriculture, connect new farmers with mentor farmers, and highlight producers who are implementing best practices. The partnership between Marin Organic producers association and University of California Cooperative Extension is another model of research and knowledge-transfer among farmers, University researchers, and local communities. Roots of Change and the California Food Policy Council are dedicated to promoting progressive food and agriculture policies in the state. The biophysical elements of agroecology play out at the farm-scale and landscape-scale; however, agroecology also involves scaling up to ensure environmental, economic, and social sustainability of the entire food system. Part of the agroecological transition is the "production linkage", connecting food producers and processing activities, such as The Local Harvest database of local small farms and marketing opportunities. This step is followed by the "consumption linkage", requiring investments in the manufacturing and services sectors (packaging, processing industries, retail) to support local and regional economies and food systems (De Schutter, 2010).

Education, outreach, and research all have the potential to support the paradigm shift toward sustainable agriculture if they account for and adapt to the cultural and policy landscape in which they operate (Meek, 2016). Agricultural Extension represents an avenue to engage farmers in agroecological transition, through communication and education about agroecological practices appropriate to their unique setting and crops (Meek, 2016). The Gates Foundation, Borlaug fellowships, USDA grants, and other major funders of agriculture should all incorporate an explicit focus on long-term sustainability and climate change resilience. This represents a shift away from the prevailing approach, which views agricultural systems in a vacuum without consideration of biological interactions or long term agroecosystem health and stability. While crop breeding or genetic modification can increase drought resilience at the crop genetic level, the genetic makeup of an individual crop will not ensure the ability of a farm to withstand extreme climate stressors. Instead, all agricultural programs need to approach the issue of food production by looking at the whole system and ways to maximize agroecosystem resilience.

As we have shown above, evidence exists demonstrating the resilience and yield potential of agroecology and organic systems, yet this is not the prevailing model of agriculture in the U.S. and many industrialized countries. A key reason for this is that greater support is needed to research and implement sustainable agricultural practices on a wider scale (Stapper, 2013). The U.S. can look to France as a model of a country whose government has recently prioritized a major transition to sustainable agriculture.

France's 'Law for the Future of Agriculture, Food and Forestry'

France has committed to a trajectory of change, with full state support behind an agroecological transition, enacting the 'Law for the Future of Agriculture, Food and Forestry' (Loi d'avenir pour l'agriculture, l'alimentation et la forêt) in 2014 (Assemblée nationale et Sénat de France, 2014). The Law promotes agroecology as the predominant model for French agriculture, defining agroecology as "a production system favoring/prioritizing the autonomy of farms and the improvement/enhancement of their competitiveness while decreasing the consumption of energy, water, fertilizers, phytopharmaceutical products and veterinary medications" (Loi n° 2014-1170, Article 3; author's translation). This legislative framework seeks to combine economic, environmental and social performance of farms (articles 17–25). The French agroecological transition started before the 2014 Loi d'avenir. In 2012, the government began funding on-farm research projects and promoting agroecology, with the goal of transitioning the majority of agricultural holdings in France to agroecological practices by 2025 (Trabelsi et al., 2016). In 2014, a total of 6.7 M Euros were allocated to 3,300 farms to experiment with innovative agroecological approaches for two to three years (French Ministry of Agriculture, Food and Forestry, 2014[3]).

A pivotal feature of the Loi d'avenir are the Economic and Environmental Interest Groups. Economic and Environmental Interest Groups (EEIG) consist of regional groups of farmers and other stakeholders organizing to share information, to collectively implement agroecological production practices tailored for their region, and to attract governmental funding (Monteduro et al., 2015). The EEIG units are expected to be the catalyst for the agroecological transition through their community-based initiatives. Partnerships between farmers and expert researchers have also encouraged knowledge-transfer. For example, entomologist and agroecologist Jean-Philippe Deguine from the French Agricultural Research for Development Center (CIRAD) worked with fifteen producers in Réunion to eliminate insecticides in mango production (Della Mussia, 2016). Farmers were involved in project development and received trainings, including a university professional qualification certificate.

The French government has coupled these grassroots, farm-based efforts with the use of technological innovations (robotic and digital systems), information systems, agricultural big data and simulations. The high level of technical knowledge required may present a challenge for and create resistance from some farmers (Chantre and Cardona, 2014), but an effective EEIG system can encourage these farmers to learn from early adopters. The French Ministry of Agriculture is monitoring progress, reporting successes, and continuing to support agroecology projects (Le Foll, 2016), including funding the development of a model to monitor and evaluate progress (Trabelsi et al., 2016). Using data collected from farms engaged in the agroecological transition, the model assesses performance and simulates downstream effects of changes. Beginning in 2017, an additional 10 billion Euros will be invested in projects related to agroecology education, research, innovation, and business development.

An agroecological transition at a national level is not a spontaneous linear process, and the French system still has some inefficiencies as discussed by Chantre and Cardona (2014) and Arrignon and Bosc (2015). Some themes found in their reflections are applicable to other contexts, including the U.S.:

- The need for an improved systemic vision with a synergistic collaboration among administrative services/agencies, local entities and farmers.
- The recognition of challenges farmers face in changing their practices: costs (Wilson and Tisdell, 2001), commitment to multistep (progressive) process over multiple years, and willingness to diversify practices and learning strategies.
- The potential conflict between short-term public policy agenda and long-term nature of the transition to agroecological practices at the farm level.
- Market regulations and the guarantee of resilient livelihoods (De Schutter, 2010; Purvis et al., 2012; Seufert et al., 2012)

An open dialogue around the challenging aspects of the legislative process is crucial to building a solid foundation for national transitions. The agroecological transition is expected to go through trials and errors and to evolve by the cumulative learning of all involved (Duru et al., 2015). The work of identifying and improving on the challenging aspects of the French agroecological transition can be seen as a genuine effort towards building a successful statewide transition. It stimulates constructive debates (even around the definition of agroecology, Arrignon and Bosc, 2015, pp. 8–14) and provides guidelines for participatory action among scientists, policymakers and farmers. This legislation represents the beginning of a large-scale progressive change, and France serves as an example of a country moving beyond short-term fixes to a commitment to a fundamental paradigm shift.

Conclusion

We have shown that diverse agroecosystems and organic agriculture are more resilient to extreme weather events, which is essential in light of California's current situation and the expected effects of climate change. Our focus on drought in California as a potential catalyst for reform illustrates how agroecological principles can apply to any region and to other climate extremes and uncertainty. It is important to recognize that building adaptive capacity in any region or production system will require government support for changing agricultural practices (Walthall et al., 2012). Agroecological farms can be more productive than monocultures and conventionally managed farms, and agroecosystem complexity builds farm resilience through healthier soils, pest and disease control, and microclimate control. This can help maintain yields, decrease costs, and increase soil health and long-term production capacity. Altering water and land use by the agricultural sector will not occur voluntarily given how entrenched our current system is; it will require financial incentives and technical support for farmers to transition toward sustainable practices.

We discussed problems with the dominant agricultural model in the face of ongoing drought in California and other extreme climate conditions. This reveals that the U.S. has not learned enough from the past as our food system is not adequately prepared for crisis driven by climate change. This paper asserts the importance of acting on two fronts: creating laws in support of agroecology and natural resource conservation, as well as providing financial support and outreach for growers to make this transition. Agroecological approaches integrate knowledge and experience from farmers and mimic ecosystem complexity to ultimately build resilience in farming systems. As co-leaders, farmers and farmer organizations contribute valuable experiential knowledge and insights. Farmer knowledge is one of the foundations on which the agroecology model is built. Sustainable agriculture practitioners and organizations should be integral in guiding policy and throughout the transition processes. The new French legislation is in fact mobilizing a shift towards a culture where farmers are recognized as valued leaders in a healthy and functional society. Given the shortcomings of industrial agriculture, agroecology is a promising "next frontier" in the agriculture story. Looking back at the lessons learned from the U.S. Dust Bowl of the 1930s, we recall that the U.S. Farm Bill was created to support struggling farmers, minimize rural poverty and hunger, and incentivize conservation agriculture. It is time to revisit the purpose of the U.S. Farm Bill to reflect a view of farming as land stewardship and food production, rather than mass production of a small number of crops. We urge U.S. policymakers to turn this period of water scarcity into opportunity—opportunity to harness political will and public support for a true paradigm shift in agriculture.

Notes

1. See: https://landinstitute.org/ for resources and publications.

2. Though Cuba's political structure and system of land rights are distinct from the U.S., the case of Cuba shows that agroecological transition can occur at a national scale. Lessons can be taken from Cuba on the effectiveness of government support for agroecological research and dissemination.

3. The French Ministry of Agriculture website provides an interactive map of the 103 projects across the country.

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- Contributed to conception and design: KSM, GB
- Drafted and/or revised the article: KDM, GB
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Competing interests

The authors are not aware of any competing interests.

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