frontiers | Frontiers in Agronomy

TYPE Review
PUBLISHED 07 February 2025
DOI 10.3389/fagro.2025.1534370

EDITED BY
Sylvia H. Vetter,
University of Aberdeen, United Kingdom

REVIEWED BY
Aritz Royo-Esnal,
Universitat de Lleida, Spain
Mashford Zenda,
University of the Free State, South Africa

*CORRESPONDENCE
Miguel A. Altieri
agroeco3@berkeley.edu

RECEIVED 25 November 2024
ACCEPTED 15 January 2025
PUBLISHED 07 February 2025

CITATION
Altieri MA, Nicholls CI, Montalba R, Vieli L and Vazquez LL (2025) Agroecology and the limits to resilience: extending the adaptation capacity of agroecosystems to drought. *Front. Agron.* 7:1534370.
doi: 10.3389/fagro.2025.1534370

Agroecology and the limits to resilience: extending the adaptation capacity of agroecosystems to drought

Miguel A. Altieri[1]*, Clara I. Nicholls[2], Rene Montalba[3], Lorena Vieli[3] and Luis L. Vazquez[4]

[1]Department of Environmental Science, Policy, and Management, University of California, Berkeley, Berkeley, CA, United States, [2]Global Studies, University of California, Berkeley, Berkeley, CA, United States, [3]Departamento de Ciencias Agronomicas y Recursos Naturales, Universidad de la Frontera, Temuco, Chile, [4]Centro Latinoamericano de Investigaciones Agroecologicas (CELIA), Medellin, Colombia

Given the unpredictability, increasing frequency and severity of climatic events, it is crucial to determine the adaptation limits of agroecological strategies adopted by farmers in a range of environments. In times of drought many smallholders' farmers cope with stress using a series of crop diversification and soil management strategies. Intercropping and agroforestry systems complemented with mulching and copious organic matter applications can increase water storage, enhancing crops' water use efficiency. Although an overwhelming number of studies demonstrate that these agroecological designs and practices are associated with greater farm-level resilience, it is important to recognize the limits of resilience. The aim of this paper is to assess the limitations of agroecological practices in enhancing the ability of agroecosystems to adapt to climate change under extended drought stress which may overwhelm crops' adaptation response. A set of agroecological practices that can extend such limits under prolonged water stress scenarios are described. Two methodologies to assess farms' resilience to drought provide useful tools, as they can assist farmers and researchers in identifying the practices and underlying mechanisms that reduce vulnerability and enhance response capacity allowing certain farm systems to better resist and/or recover from droughts. Clearly, reducing farmers exposure to drought requires collective actions beyond the farm scale (i.e. restoring local watersheds to optimize local hydrological cycles) aspects not explored herein. When climatic events are compounded by uncertainties imposed by external economic and political conditions, farmers' abilities to overcome adversity may be reduced, emphasizing the importance of policy support, a dimension beyond the scope of this review.

KEYWORDS

drought, limits of resilience, agroecology, adaptation, mulching, soil organic matter, diversification

1 Introduction

Earlier than predicted by the scientific community, the world is already facing a series of extreme climatic events (droughts, hurricanes, floods, heat-waves, sea level rise, etc.) that threaten agricultural production and food security in many regions of the world. Modern agricultural systems characterized by monocultures linked to pesticides and transgenic crops are not shifting in ways that will protect such simplified systems from current and expected shifts in climate change. Rather, specialization and intensification pressures driven by short-term economic benefit, force farmers towards specialization and intensification at significant risk to long-term agricultural stability (D'Agostino and Schlenker, 2016). On the other hand, droughts, storms and floods pose a significant threat to more than 475 million smallholder farmers who despite in producing 50-70% of the world's food are very vulnerable to climate change as most live in fragile landscapes (hillsides, flood plains, etc.) and who have few assets to fall back and limited ability to recover from intense climatic events (Lobell and Gourdji, 2012). As long as these socio-economic trends hold into the future, maintaining crop productivity in large and small farms in the face of anticipated climatic events will be a major challenge.

Emerging evidence suggests that increasing the diversification of agricultural systems at the field and landscape level, and enhancing soil organic matter and biological activity, are key strategies to improve the resilience of agricultural systems to climate variability (Altieri et al., 2015). Although the overwhelming majority of studies demonstrate that agroecological designs and practices are associated with greater farm-level resilience protecting farmers against climatic extremes, it is important to recognize the limits of resilience. The ability of agroecosystems to adapt to climate change has limits delineated by capacity thresholds, after which climate damages begin to overwhelm the adaptation response. Even with scaled-up adaptation strategies, the limits of adaptation can often be reached under prolonged and severe climatic stress (Kragt et al., 2013).

Given the unpredictability, increasing frequency and severity of climatic events, it is crucial to determine the adaptation limits of agroecological strategies adopted by farmers in a range of environments. A strong hurricane or prolonged drought could lead to farming system degeneration and failure. The adaptation limit threshold for each farm, the pathways of degradation or failure, and whether the climate impacts suffered represent temporary (recoverable) or permanent losses, will depend on the agroecological features of each farm such as levels of crop diversity, genetic diversity, landscape matrix, soil organic matter, as well as farmers responsive capacity (Córdoba et al., 2019).

Building on what is already known about the degree to which farmers can adapt to a changing climate, the goal of this article is to try to understand and define where and when limits to adaptation to drought can be reached in a particular agro-landscape. Many adaptation measures have been suggested to reduce the vulnerability of farmers to prolonged droughts, but the extent to which those can be efficiently extend and/or postpone threshold limits under severe and prolonged water stress is not known.

2 Impacts of droughts

Industrial agriculture which occupies about 70- 80% of the global agricultural surface, is part of the problem by emitting no less than 30% of greenhouse gases. On the other hand, large-scale monocultures which dangerously reduce crop genetic and species diversity, exhibiting a high level of ecological homogeneity, makes them particularly vulnerable to climate change (NRC, 1972). In the late twentieth century in the USA, 60–70% of the total bean area was planted with 2–3 bean varieties, 72% of the potato area with four varieties, and 53% of the cotton area planted with three varieties, demonstrating how modern agriculture is shockingly dependent on a handful of varieties for its major crops (Robinson and Wallace, 1996). This fragile ecological status of industrial agriculture represents a major threat to humanity's food security.

The estimated global yield loss each year due to drought is estimated at around USD 10 billion. Severe droughts cause substantial decline in crop production leading to 21 and 40% yield reductions in wheat and maize when grown in monocultures, which is the norm (Daryanto et al., 2017). Vulnerability to droughts was evidenced in the United States in 2012, when the worst drought in 50 years occurred, severely affecting crop production in 26 of the 52 states and covering at least 55% of the U.S. land area. In the US Midwest, specialization in rain-fed maize and soybean production, makes this region increasingly sensitive to drought, leading in 2012 to reduced maize yields by ~25% (Boyer et al., 2013).

After four years of drought in California (2011-2015), large areas of land (more than 250,000 hectares) were removed from cultivation due to lack of water, representing losses of US$1.8 billion and a reduction of 8,550 jobs. In 2014, harvested acreage was 6.9 million acres lower than at any time in the past 15 years and crop revenue declined by US $480 million (Cooley et al., 2015).

On the other hand, resource poor farmers living in vulnerable landscapes are particularly sensitive to climate change. Recent studies suggest that by 2025 climate stress may reduce bean production in Central America by more than 20% and maize yields by as much as 15%. In Honduras, the predicted production losses could amount to about 120,000 t annually, valued at about US$40 million (Eitzinger et al., 2012). The 2014-2016 drought in the dry Pacific region of Central America resulted in 1.6 million people becoming food insecure and 3.5 million in need of humanitarian assistance. The projected mean precipitation decrease will be accompanied by more frequent dry extremes in all seasons, leading to grain yield reductions in Mexico up to 30% by 2080 (Donatti et al., 2019). The most climatically vulnerable are small-holders who farm on steep lands with thin soils, depending on rainfed agriculture while lacking technical and/or financial support. In addition, poor rural households have difficulty coping with climate change where infrastructure (equipment and roads) is inadequate, access to natural resources (water and land) is limited and social capital and government support is weak.

3 Efforts to build resilience

Despite the serious effects of climate change on small-scale agriculture, data from model predictions often ignore the adaptive capacity of small farmers who use several agroecological strategies and socially mediated solidarity networks to cope with and even prepare for extreme climatic variability. Many researchers have found that despite their high-exposure sensitivity, indigenous people and local farming communities are actively responding to changing climatic conditions and have demonstrated their resourcefulness and resilience in the face of climate change (Morton, 2007).

Strategies such as maintaining crop genetic and species diversity in fields and herds provide a low-risk buffer in uncertain environments (Gil et al., 2017). A review of 172 case studies and project reports from around the world shows that agricultural biodiversity contributes to resilience through a number of strategies that are often combined: the protection and restoration of watersheds, the sustainable use of soil and water resources, agroforestry, diversification of farming systems, various adjustments in cultivation practices and the use of stress-tolerant crops (Mijatovic et al., 2013).

4 Adapting to droughts

Most farmers efforts to cope with drought are usually directed at minimizing risk. Scaling back on production which involves a reduction in the size of the cultivated area, by as much as 25%, or establishing “protected” community gardens are common adaptive responses after a drought. In times of drought many smallholder farmers cope with stress planting more root and tuber crops, increasing consumption of fruits to replace lost basic grains, selling fire wood and animals as an alternative income source, reducing food consumption, selling crops for lower prices, and seeking help from governments and other organizations (Harvey et al., 2018).

A common strategy is resorting to wild food harvest such as weeds that in Meso America, traditional farmers usually call “quelites or arvenses”, important sources of vitamins, minerals and protein (content of edible wild plants can usually range from 1.3% to 7.5% of freshweight) thus improving the nutritional quality of local diets (Ebel et al., 2024). In Tlaxcala Mexico a typical milpa system may produce up to 13.2 tons of quelites, each family consuming 3 kg 2-3 times/week. This is important in time of crop failure due to drought, where certain weed species of the genus *Portulaca, Amaranthus* and *Chenopodium* are more tolerant than maize and beans to water stress (Altieri and Trujillo, 1987).

In dry environments, farmers who are fortunate to experience a small level of rainfall and are able to harvest some water from roofs and catchment areas, an option is to establish small areas with new, off-season vegetables using the limited collected water. Drought adaptation measures also include choosing sturdier varieties and shifting to other crops entirely, to adopting/improving irrigation systems. In sub-Saharan Africa much emphasis has been given to promoting ancient crops which exhibit drought tolerance such as teff, fonio, various millet varieties, sorghum, cassava and several legumes species such as pigeon peas and cowpeas.

Measures directed at breaking vulnerable monocultures imply a redesign of the farming system which includes adoption of soil management practices such as using a thick layer of mulch and copious applications of compost, to diversification practices such as intercropping and agroforestry systems. Natarajan and Willey (1986) examined the effect of drought on enhanced yields with polycultures by manipulating water stress on intercrops of sorghum and peanut, millet and peanut, and sorghum and millet. All the intercrops over-yielded consistently at five levels of moisture availability, ranging from 297 to 584 mm of water applied over the cropping season. Quite interestingly, the rate of over-yielding actually increased with water stress, such that the relative differences in productivity between monocultures and polycultures became more accentuated as stress increased.

Many intercropping systems also improve the water use efficiency compared to monocultures. Water-utilization efficiency by intercrops usually exceeds that of sole crops, often by more than18% and sometimes by as much as 99%. They do so by promoting the full use of soil water by plant roots, increasing the water storage in the root zone, and reducing inter-row evaporation, but also by controlling excessive transpiration and creating a special microclimate advantageous to plant growth and development (Lithourgidis et al., 2011).

Higher resistance to drought may be more common in cropping systems that exhibit higher levels of soil organic matter content, which in turn enhances the soil’s moisture holding capacity, leading to higher available water for plants, which positively influences resistance and resilience of crop plants to drought conditions. Hudson (1994) showed that as soil organic matter content increased from 0.5% to 3%, available water capacity more than doubled. Mulching is central to farmers’ adaptation to dry conditions which helps conserve soil moisture by reducing evaporation, thereby more moisture is accessible near the plant roots, extending the time for plants to absorb water (Sharma and Bhardwaj, 2017).

Agroforestry systems buffer crops from large fluctuations in temperature (Lin, 2011), thereby keeping the crop closer to its optimum conditions. Shaded coffee systems have shown to protect crops from decreasing precipitation and reduced soil water availability because the over story tree cover is able to reduce soil evaporation and increase soil water infiltration (Lin, 2007).

Larger scale farmers may adapt to stressful growing conditions by adopting diversified rotations. A recent study showed that a 7% higher maize yield during hot and dry years in a diversified five-crop rotation than in a simpler maize-soybean rotation. Such gains resulted from improved soil properties, such as increases in soil water capture and storage and abundance of beneficial soil microbes (Renwick et al., 2021). More diverse rotations also showed positive effects on yield under unfavorable conditions, by reducing yield losses from 14.0%–89.9% in drought years. Analysis of 11 long-term experiments comprising 347 site-years and ~11,000 observations across the US and Canada showed that crop-rotational diversity can reduce the risk of low maize yields during droughts (Bowles et al., 2020). Another strategy commonly used by commercial farmers is the use of cover crop mixes planted before the main grain crop. A mix of rye, hairy vetch, crimson clover planted before corn, exhibited 20 mm greater soil water storage compared to no cover crop before corn. Estimated evapotranspiration was lower for systems with cover crop mix, exhibiting also greater estimated infiltration rates (Schomberg et al., 2023).

Farmers can rely on three strategies against drought stress: plant escape, avoidance and tolerance, involving mechanisms that range from early crop flowering to increase of water uptake from well-established root systems (Fahad et al., 2017). Figure 1, lists the most effective agroecological strategies with potential to enhance such mechanisms.

5 Methodologies to assess resilience of agroecosystems to drought

Resilience is defined as the ability of an agroecosystem to absorb disturbances while retaining its organizational structure and productivity due to its ability to adapt to stress and change following a perturbation (Cabell and Oelofse, 2012). Thus, a "resilient" agroecosystem would be capable of providing food production, when challenged by a severe drought. Researchers have developed methodologies aimed at assessing the resilience of agroecosystems by estimating its vulnerability (refers to the degree to which an agroecosystem is susceptible to the impacts of drought) and the response capacity (ability of both farmers and their farming systems to mitigate, resist and recover from threat like drought). Vulnerability decreases resilience while higher response capacity enhances it, therefore farms exhibiting low vulnerability and high response capacity values are considered more resilient (Altieri et al., 2015). Two of such methodologies are presented below.

5.1 Cuban case study

A study of the perception of farmers and local technicians on sensitivity to drought, was carried out on three integral farms (livestock-agriculture-forestry) undergoing agroecological transition, located in suburban areas of the province of Havana, Cuba: "La Victoria" (24.48 hectares, Marianao municipality), "Media Luna" (6.5 hectares, Habana del Este municipality), "La China" (7.10 hectares, La Lisa municipality) (Vázquez et al., 2015).

To determine the resilience of farms to drought, the resilience capacity (RCd) provided by specific agroecological designs and management practices was contrasted with the sensitivity to drought expressed by natural resources (SNRd) (Vázquez et al., 2016). The drought resilience capacity (RCd) was determined using the following indicators:

5.1.1 Resistance-absorption

Ability of the agroecosystem to resist-absorb the physical and prolonged effects of drought, which was determined by indicators such as: complexity of the landscape matrix, complexity of the production system, composition of agrobiodiversity, level of soil cover, soil management practices, water access, and design of cropping and livestock systems.

5.1.2 Recovery

Ability of the agroecosystem to return to the productive state prior to the incidence of the event, calculated using state of the productive infrastructure, availability of means of production, capacities of the support infrastructure, reduction of external energy, capacity for self-sufficiency in food and labor, capacity for food self-sufficiency for working animals, capacity for integrating bioinputs for crop nutrition and health of crops and animals, as indicators.

5.1.3 Transformability

Capacity of the production system to achieve resilience capabilities influenced by public policies and the adaptability capabilities and skills of farmers. It is assessed through the following indicators: level of education of workers, gender and generational equity, capacity for self-organization, benefits for workers, participation in reciprocal exchanges, behavioral perception of the principles of agroecology, participation in innovations, capacity for management of financing, level of productive stability, level of biosafety, access to agricultural extension services. RCd values above 0.50 indicate that the

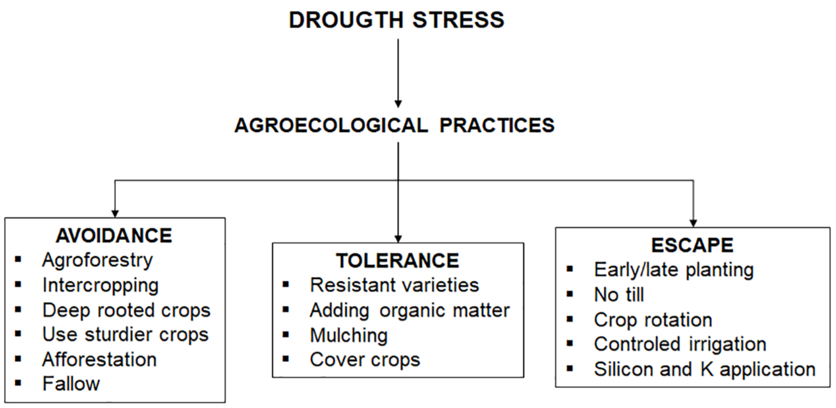

FIGURE 1
Agroecological practices commonly used to implement the strategies of avoidance, tolerance and escape from droughts.

production system is starting to exhibit drought resilience capabilities; values around 1.0 denote advancement towards a state of resilience and values above 1.5 evidence high resilience capabilities.

5.1.4 The sensitivity of natural resources

The sensitivity of natural resources (SNRd) was determined through two components and their respective indicators: exposure to the event (drought frequency and duration) and sensitivity of crops, animals, soil and water supply. SNRd was considered very high when the value obtained was above 0.8; high for values between 0.6- 0.8; medium when values ranged between 0.4-0.59; low when values 0.2-0.39 and very low below with values < 0.2.

The three farms exhibited similar resistance-absorption values (between 0.59 and 0.72) and was limited mainly by the low structure of the production system matrix and poor spatial/temporal design of crop and livestock systems. “La Victoria” farm (0.27) and “Media Luna” (0.42) showed low recovery values due to lower availability of means of production, lower infrastructure and low food self-sufficiency for people and animals. ”La China” (0.72) exhibited higher recovery values due to greater infrastructure, access to inputs and food self-sufficiency. Transformation ability was greater for the “La China” farm (0.79), followed by “Media Luna” (0.61) and “La Victoria” (0.51). The variables that most limited transformability were: lack of self-organization and finance management, low productive stability and access to extension services.

The General Resilience Index to droughts (GRId) was determined with the following equation: GRId=RCd/SNRd (Vázquez et al., 2019). In summary the lowest drought resilience capacity was exhibited by farm La Victoria (GRId=0.66). The GRId for Media Luna was 0.93 (medium) and La China exhibited a high GRId value 3.21) reflecting high resilience capacities (values above1.5). The three farms are above the drought resilience threshold (GRId >0.5), evidencing that production systems under agroecological transition acquire resilience. In the three studied farms, the drought resilience capacity (RCd) is inverse to the sensitivity of natural resources (SNRd) of productive importance such as crops, animals, soil, water supply. Clearly results indicate that as resilience capabilities increase, sensitivity decreases (Figure 2).

5.2 Chilean case study

In the Araucania region of Chile, socio-ecological resilience was evaluated in 177 peasant farming systems differentiated by the cultural ethnicity of the farmers: Mapuche, Chilean and descendants of European settlers, located in an area where droughts are increasing in frequency and intensity due to climate change (Montalba et al., 2015).

Using a series of indicators defined in a participatory manner, farm resilience was estimated based on vulnerability of farms to drought and on the response capacity of farmers. Vulnerability indicators included (1) water access difficulty, (2) area of forest plantations around farms, (3) cultivated homogeneity (crop diversity) and (4) farm location within the watershed. Drought response capacity was estimated by indicators such as (1) farmers knowledge of agricultural practices to withstand droughts, (2) conservation and use of drought-resistant crop varieties, and (3) water-related social networks. Indicators were assessed using a range of sampling techniques, including individual and group interviews, socio-economic surveys, landscape analysis using GIS tools, review of farm records and direct measurements on farms (Montalba et al., 2015). The influence of ethnicity was assessed using the Tukey HSD (Tukey Honest Significant Difference) *post-hoc* test. The presence of spatial autocorrelation in the values for each variable analyzed was assessed using the Mantel test with 999 iterations. All statistical analyses were performed using R v.2.15.0.

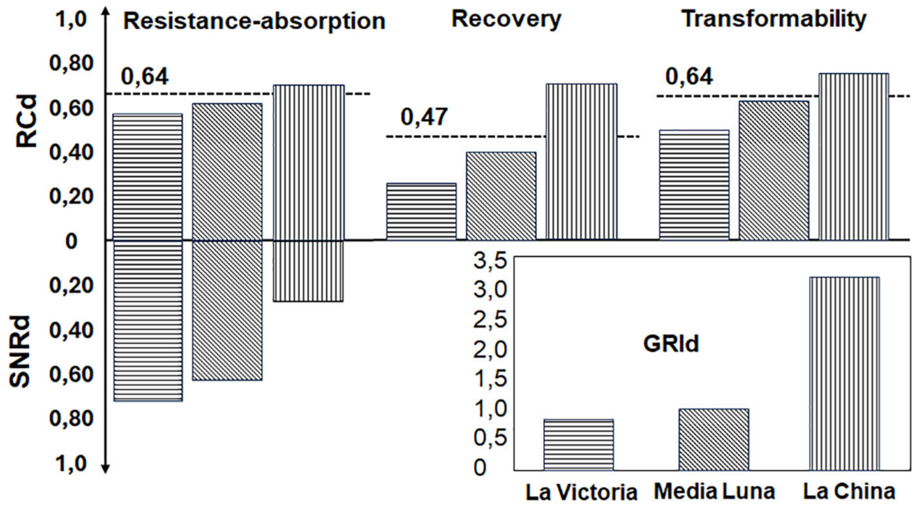

FIGURE 2
Summary of results from indicators applied to three suburban farms in La Habana, Cuba. Estimating Resilience Capacity to Drought (RCd), Sensitivity of Natural Resources (SNRd) and the General Drought Resiliency Index (GRId) (Vázquez et al., 2019).

The estimated resilience value was higher in Mapuche farms with a mean value of 0.88 (0,2.7) [optimal value around 1,5], while in Chilean and European farms resilience values were 0.52 (0, 1.38) and 0.55 (0,1.97) respectively. As observed in Figure 3, Mapuche farmers exhibited lower levels of vulnerability, possibly due to their lower proximity to pine/eucalyptus plantations in a radius of 1 km and greater crop diversity compared to Chilean and European settler farms. Mapuche farms also showed higher capacity to cope with drought, due to their command on various drought ameliorating practices and the use of tolerant crops and varieties. Chilean farms exhibited higher levels of water-related social networks, facilitating their access to declining water supplies, but the homogeneity of their agrolandscapes made them more vulnerable. Results suggest a greater resilience of Mapuche farming systems to drought, which is closely linked to their crop diversity, maintenance of traditional knowledge and practices and the conservation of local varieties and seed exchange.

The results underline the importance of agricultural biodiversity and traditional practices in improving resilience to climate change. Although modern agricultural policies often undervalue these systems, this study shows that traditional agricultural practices, rooted in indigenous and farmers' knowledge, contribute to the resilience of agricultural systems and to food security in times of hydric stress.

6 The limits of resilience

It is important to identify the limits of resilience before an agroecosystem subjected to an extended climatic stress reaches the tipping points (thresholds) that lead to potential long-term or irreversible consequences (Huang et al., 2022). Observations in Central America and the Caribbean after recent hurricanes showed that in general agroecological farms coped better than conventional farms. However in areas with steeper slopes, the difference in agroecological resilience between diversified farms and conventional monocultures were less clear as the combination of rainfall intensity and slope became so great that differences in resilience between the two types of farms were no longer apparent. Although factors such as exposure, farm design and management practices mitigated impact, on average agroecological farms suffered as much damage as conventional farms (Holt-Giménez, 2002). Similarly in Cuba, highly diversified farms close to the coast, suffered high levels of damage due to their extreme exposure to rains, winds and sea penetration caused by Hurricane Irma (Vázquez, 2021).

In Puerto Rico, the resilience usually associated with the shade coffee systems was "cancelled" during the dramatic disturbance caused by Hurricane Maria in Puerto Rico, a phenomenon that may occur more commonly as climate change continues its course (Perfecto et al., 2019). Similarly, in areas affected by prolonged droughts and in the absence of irrigation, it doesn't matter how much organic matter is added to the soil to store water, or how much soil is covered with mulch to prevent evaporation, most crops succumb after a prolonged water stress (Tyagi et al., 2020).

This "cancelation of resilience" occurs when the severity and length of the climatic event pushes the agricultural system from one stable state to a deteriorating one. Determining the limits of resilience is not only key to assess impacts of climate change but it is also a precondition to define effective climate change adaptation strategies.

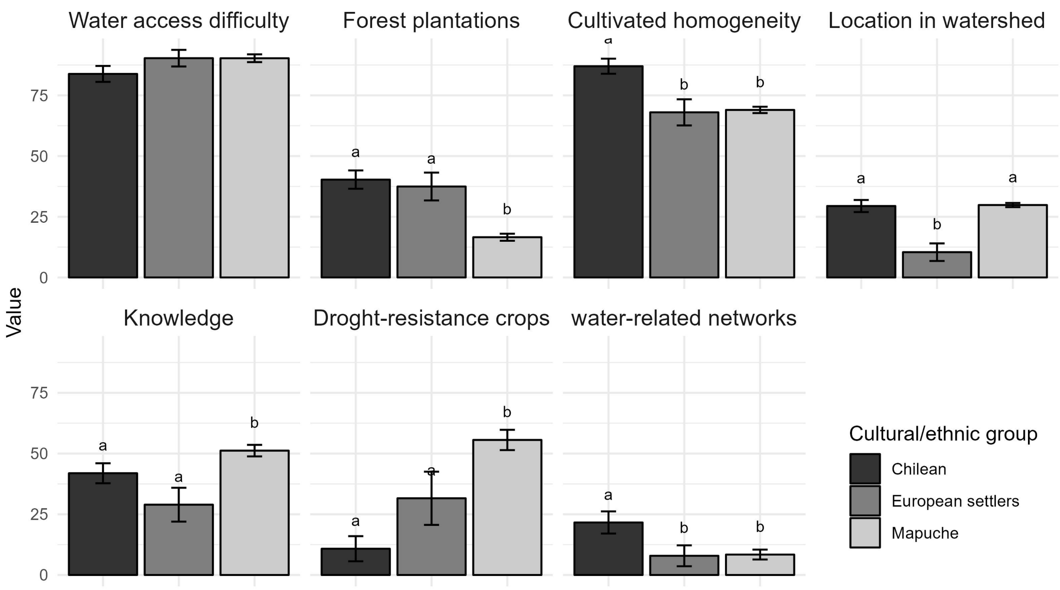

FIGURE 3
Variables used to estimate levels of vulnerability (first row of bar graphs) and drought response capacity (second row). In each bar graph, higher values indicate higher vulnerability to drought or greater drought response capacity in the various farmers grouped by cultural/ethnic origin in the Araucania region, Chile (Montalba et al., 2015). Lower-case letters are used to establish if the values represented in bars are or are not significantly different. Two bars with the same letter are not statistically different, bars with different letters are.

7 Extending the drought resilience limits

In rainfed farms affected by drought, a desirable range of soil moisture values should be maintained, in order for the system to continue functioning. It is important to set moisture limits for defined crop/environment situations, beyond which the system becomes unsustainable when it exceeds a designated trigger or threshold level (Morison et al., 2008). But more critical and of practical importance for farmers, it is to define whether a set of agroecological practices can extend such limits under prolonged water stress scenarios. In other words, is it possible to postpone the “resilience cancelation period”?

One key strategy is surface mulching which can optimize the partitioning of the water balance components, increasing moisture storage, leading to increased and water use efficiency (WUE) thus extending the crop cycle of low water requiring cropping systems (Lal, 1974). In most cases soil moisture content is directly linked to the degree of mulch cover. A study found that a 5 cm mulch depth minimized evaporation by 40%. An enhancement in mulch depth to 10 cm increased soil moisture by 10%, while a further boost (to 15 cm) provided no additional benefit. In north west India, straw mulching (6 t ha^{-1}) reduced soil water evaporation component of evapotranspiration (ET) by 18.5 to 23.8 cm in a range of crops, but it is not known how such reductions extended the crop growing period under drought (Jalota and Arora, 2002). One study found that zero tillage with residue retention buffered crops from short drought episodes and the extra 20 mm water that were available corresponded to the evapotranspiration requirements for 5 to 6 days of crop growth potentially extending the possibility of crop growth an extra 10-12 days in the absence of irrigation (Doorenbos and Kassam, 1979).

Under Mediterranean conditions, surface coverage with a mulch layer is an important water conservation practice with many studies reporting higher water storage over summer and decreased soil water evaporation, giving crop roots time to extract a greater proportion of the water from the surface soil. Soil water evaporation losses can be decreased over periods shorter than 14 days, provided that a 70%, or higher, shading is maintained through mulching practices. In order to obtain a 70% ground, cover a minimum of 6000 kg crop residue ha^{-1} may be required (Beukes et al., 2004).

Mulching also improves root development leading to 30-50% gain in root weight compared to non-mulched crops. It is common to observe larger volume of root-permeated soil, enhanced lateral root extension and deeper root penetration after mulch application. Obviously extended and deeper root systems more fully explore the soil profile in search for hygroscopic water. Therefore, crops with deeper roots can better withstand a drought than crops with superficial root systems (Lal, 1978).

An unappreciated phenomenon is the fact that mulching positively influences soil biota, as soil cover improves environmental conditions for soil organisms by increasing organic matter as a food source for microorganisms, invertebrates and earthworms. Straw and grass mulch significantly increased the amount and biomass of earthworms, organisms known to be effective in mixing the digested mulch material in the soil thereby improving soil structure and porosity. Researchers have observed maize roots to follow a stable worm channel to more than 120 cm depth. More lateral root spread under mulched strips was at least partially due to the sponge-like structure created by worm activity. It has also been observed that some mulches enhance naturally occurring mycorrhizae populations, and that water supply to crops is improved through mycorrhizal infection, allowing plants to better tolerate water stress (Jodaugienė et al., 2010).

Soils in dry climates have frequently low soil organic matter (SOM) content. Restoring soil organic matter can increase plant available water capacity in the root zone. Thus, addition of organic matter in the form of manure or compost, can significantly improve soil aggregation, macropores, lower bulk density and improve water retention and hydraulic conductivity (Magdoff and Weil, 2004). In fact, soils with low SOM content (0.5-1.0%) a 1% increase in SOM content in the 0–20 cm depth would increase available water to crops by 3– 4 mm. For soils with higher SOM content 2->3% the available water increase would range from 1- 2 mm, suggesting that the water storage effects of SOM are more effective in organic matter poor soils (Lal, 2020).

The available evidence indicates that the combination of mulching and SOM addition can increase plant available water capacity in the root zone and enhance a crop’s tolerance to short-duration drought during the growing season (Zaongo et al., 1997). The effects of these strategies suggest that it is possible to extend the resilience limits but that long-term moisture conservation during prolonged dry periods may be less feasible. Clearly different agrocological practices have varied effects on soil water retention capacity. Table 1 presents a list of various adaptation measures available for farmers to cope with drought conditions. Based on current knowledge on the impact of each practice to ameliorate drought impacts (Sinclair et al., 2019; Seleiman et al., 2021) each practice is ranked according to its potential (high, medium or low) to extend the resilience threshold. Out of 15 practices, eight exhibit high potential to extend the limits of resilience to drought.

8 Conclusions

Climatic threshold refers to the levels of climatic factors (i.e. intensity and length of a drought) that can push an agricultural system from a relatively stable state to a deteriorating one. Determining the climate threshold for agricultural production under drought stress is not only key to assess climate change impacts but also to determine the types of adaptation strategies (Juhola et al., 2024).

TABLE 1 Potential of various agroecological practices in extending the limits of resilience to drought.

Practices	High	Medium	Low
Afforestation of field edges		✓	
Crop-animal integration		✓	
Crop rotation		✓	
Intercropping	✓		
Crop variety mixtures		✓	
Agroforestry	✓		
Timely sowing in climates where crop growth partially or largely coincides with a dry season.		✓	
Use of organic manure, compost, crop residues, etc.	✓		
Mulching	✓		
Planting of cover crops		✓	
Fallow practices			✓
Using seed coating to reduce risks associated with seed desiccation	✓		
Collecting water individually from roofs and catchment areas, water reservoirs, mini dams and wells	✓		
Introducing new, off-season vegetable production using water collected in wells and mini dams.	✓		
Applying a controlled amount of water for irrigation in key crop growth periods	✓		

✓ is used to denote if the practice has a high, medium or low impact in extending the drought tolerance.

The identification and assessment of current and projected future adaptation limits is essential for stabilizing food production with agroecological strategies. Resilience limits are likely to often be breached as droughts will become increasingly severe, widespread, and frequent. Current knowledge is far from understanding when and where limits will be reached and surpassed. Given such uncertainty, precautionary and transformational adaptation of agroecosystems requires a preventive approach based on agroecological principles.

Although there is an urgent need to adapt agroecosystems to changing climatic conditions, it is important to recognize the limits to such adaptation. Scientific evidence suggests that limits to adaptation may be extended beyond the established thresholds. The literature suggests that mulching and copious SOM applications can clearly extend crop growth periods under extended drought periods, but there is a limit if the event is too prolonged.

The adoption of some of the agroecological management strategies described herein allows farmers to offset impacts in a changing climate and are key to adaptations that can support livelihood outcomes such as food security by enhancing soil fertility, water retention, etc. These actions can enable farming systems to either recover to their previous state or evolve into more resilient systems. Either option, whether incremental (e.g., mulching or adopting cover crops) or transformative (e.g., transitioning from monoculture to diverse farming) is dependent on farmers' adaptive capacity—resources or assets farmers have access to, which play a key role in such decisions. To enable smallholders to reduce their exposure to drought and other hazards, new collaborative mechanisms beyond the farm scale are needed to optimize local hydrological cycles, for example, restoring local watersheds are necessary; but this implies major efforts to organize and engage in collective action.

The two methodologies described herein provide useful tools to assess the factors that determine the vulnerability of a particular agroecosystem to drought, and also to identify the response capacity of farmers to ameliorate the impacts. Both methodologies are simple enough to be used by farmers to assess whether their farms can withstand a drought and what to do to enhance the resiliency of the farm. The methodologies also help in identifying the principles and mechanisms that allowed certain farm systems to better resist and/or recover from droughts, which can be disseminated to other farmers via Campesino a Campesino exchange processes.

Indeed, farmers' personal resourcefulness, ingenuity and management skills (i.e. maintenance of traditional knowledge, use of efficient practices, etc.) help them to cope with the risk and uncertainty of natural disasters. However, when such events are compounded by uncertainties imposed by external economic conditions, such as input price increase for agricultural inputs or competition from imported foodstuffs, then farmers' abilities to draw on local knowledge and experience to pull them through adversity becomes much more problematic. The resilience of farms to climate disturbances can be diminished by rural conflicts unrelated to ecology, such as the expansion of palm, sugar cane and soybean monocultures and mining, which dry up streams and aquifers, which displaces the peasants. Addressing these broader agrarian issues suggests that promoting resilience in agriculture does not only consist of disseminating agroecological management, but also in confronting the inequalities and social injustices that afflict rural areas and transforming extractive agro-export economic systems into local and resilient food systems. To build resilience and prevent the next intense drought from becoming another catastrophe, it is necessary to scale up agro-ecologically based production models, but at the same time solve the underlying problems of access to land, water and seeds and the lack of markets and conducive policies that marginalize the peasantry, as well as challenging the corporate power that controls food systems. These issue emphasize the importance of major political and socio-economic transformations including creation of enabling policies, a dimension beyond the scope of this review.

Author contributions

MA: Conceptualization, Writing – original draft. CN: Investigation, Methodology, Writing – review & editing. RM: Methodology, Writing – review & editing. LV: Methodology, Writing – review & editing. LV: Investigation, Methodology, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This study was partially funded by the Centro Latinoamericano de Investigaciones Agroecologicas (CELIA), Colombia.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Altieri, M. A., Nicholls, C. I., Henao, A., and Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.* 35, 869–890. doi: 10.1007/s13593-015-0285-2

Altieri, M. A., and Trujillo, J. (1987). The agroecology of corn production in Tlaxcala, Mexico. *Hum. Ecol.* 15, 189–220. doi: 10.1007/BF00888380

Beukes, D. J., Bennie, A. T., and Hensley, M. (2004). Optimizing soil water balance components for sustainable crop production in dry areas of South Africa. *Challenges Strategies Dryland Agric.* 32, 291–313. doi: 10.2135/cssaspecpub32.c19

Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M. A., Culman, S. W., et al. (2020). Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth* 2, 284–293. doi: 10.1016/j.oneear.2020.02.007

Boyer, J. S., Byrne, P., Cassman, K. G., Cooper, M., Delmer, D., Greene, T., et al. (2013). The U.S. drought of 2012 in perspective: A call to action. *Global Food Secur.* 2, 139–143. doi: 10.1016/j.gfs.2013.08.002

Cabell, J. F., and Oelofse, M. (2012). An indicator framework for assessing agroecosystem resilience. *Ecol. Soc.* 17, 18. doi: 10.5751/ES-04666-170118

Cooley, H., Donnelly, K., Phurisamban, R., and Subramanian, M. (2015). *). Impacts of California's ongoing drought: agriculture* Vol. 24 (Oakland, CA, USA: Pacific Institute).

Córdoba, C. A., Hortúa, S., and Leon Sicard, T. (2019). Key points of resilience to climate change: a necessary debate from agroecological systems. *Climate Dev.* 12 (6), 564–574. doi: 10.1080/17565529.2019.1664376

D'Agostino, A. L., and Schlenker, W. (2016). Recent weather fluctuations and agricultural yields: implications for climate change. *Agric. economics* 47, 159–171. doi: 10.1111/agec.2016.47.issue-S1

Daryanto, S., Wang, L., and Jacinthe, P. A. (2017). Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agric. Water Manage.* 179, 18–33. doi: 10.1016/j.agwat.2016.04.022

Donatti, C. I., Harvey, C. A., Martinez-Rodriguez, M. R., Vignola, R., and Rodriguez, C. M. (2019). Vulnerability of smallholder farmers to climate change in Central America and Mexico: current knowledge and research gaps. *Climate Dev.* 11, 264–286. doi: 10.1080/17565529.2018.1442796

Doorenbos, J., and Kassam, A. H. (1979). Yield Response to Water. FAO Irrigation and Drainage paper No. 33. (Rome, Italy: FAO), 193.

Ebel, R., Menalled, F. D., Morales Payán, J. P., Baldinelli, G. M., Berríos Ortiz, L., and Castillo Cocom, J. A. (2024). Quelites—Agrobiodiversity beyond our crops. *Elementa: Sci. Anthropocene* 12, 1–26. doi: 10.1525/elementa.2022.00141

Eitzinger, A., Läderach, P., Sonder, K., Schmidt, A., Sain, G., Beebe, S., et al. (2012). *Tortillas on the Roaster: Central America's Maize–Bean Systems and the Changing Climate* (Cali, Colombia: CIAT Policy Brief No. 6. Centro Internacional de Agricultura Tropical (CIAT), 6 p.

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., et al. (2017). Crop production under drought and heat stress: plant responses and management options. *Front. Plant Sci.* 8, 1147. doi: 10.3389/fpls.2017.01147

Gil, J. D., Cohn, A. S., Duncan, J., Newton, P., and Vermeulen, S. (2017). The resilience of integrated agricultural systems to climate change. *Wiley Interdiscip. Reviews: Climate Change* 8, e461. doi: 10.1002/wcc.461

Harvey, C. A., Saborio-Rodríguez, M., Martinez-Rodríguez, M. R., Viguera, B., Chain-Guadarrama, A., Vignola, R., et al. (2018). Climate change impacts and adaptation among smallholder farmers in Central America. *Agric. Food Secur.* 7, 1–20. doi: 10.1186/s40066-018-0209-x

Holt-Giménez, E. (2002). Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agriculture Ecosyst. Environ.* 93, 87–105. doi: 10.1016/S0167-8809(02)00006-3

Huang, N., Song, Y., Wang, J., Zhang, Z., Ma, S., Jiang, K., et al. (2022). Climatic threshold of crop production and climate change adaptation: a case of winter wheat production in China. *Front. Ecol. Evol.* 10, 1019436. doi: 10.3389/fevo.2022.1019436

Hudson, B. D. (1994). Soil organic matter and available water capacity. *J. Soil Water Conserv.* 49, 189–194.

Jalota, S. K., and Arora, V. K. (2002). Model-based assessment of water balance components under different cropping systems in north-west India. *Agric. Water Manage.* 57, 75–87. doi: 10.1016/S0378-3774(02)00049-5

Jodaugienė, D., Pupalienė, R., Sinkevičienė, A., Marcinkevičienė, A., Baltaduonytė, M., and Čepulienė, R. (2010). The influence of organic mulches on soil biological properties. *Zemdirbyste-Agriculture* 97, 33–40.

Juhola, S., Bouwer, L. M., Huggel, C., Mechler, R., Muccione, V., and Wallimann-Helmer, I. (2024). A new dynamic framework is required to assess adaptation limits. *Global Environ. Change* 87, 102884. doi: 10.1016/j.gloenvcha.2024.102884

Kragt, M. E., Mugera, A., and Kolikow, S. (2013). "An interdisciplinary framework of limits and barriers to agricultural climate change adaptation," in *20th International Congress on Modelling and Simulation*, Adelaide, Australia. 1–6.

Lal, R. (1974). Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. *Plant Soil* 40, 129–143. doi: 10.1007/BF00011415

Lal, R. (1978). Influence of within-and between-row mulching on soil temperature, soil moisture, root development and yield of maize (Zea mays L.) in a tropical soil. *Field Crops Res.* 1, 127–139. doi: 10.1016/0378-4290(78)90016-3

Lal, R. (2020). Soil organic matter and water retention. *Agron. J.* 112, 3265–3277. doi: 10.1002/agj2.20282

Lin, B. B. (2007). Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. *Agric. For. Meteorology* 144, 85–94. doi: 10.1016/j.agrformet.2006.12.009

Lin, B. B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience* 61, 183–193. doi: 10.1525/bio.2011.61.3.4

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., and Vlachostergios, D. (2011). Annual intercrops: an alternative pathway for sustainable agriculture. *Aust. J. Crop Sci.* 5, 396–410.

Lobell, D. B., and Gourdji, S. M. (2012). The influence of climate change on global crop productivity. *Plant Physiol.* 160, 1686–1697. doi: 10.1104/pp.112.208298

Magdoff, F., and Weil, R. R. (2004). "Soil organic matter management strategies," in *Soil Organic Matter in Sustainable Agriculture*, eds. F. Magdoff and R Weil. (Boca Raton, FL, United States: CRC Press).

Mijatovic, D., Van Oudenhoven, F., Eyzaguirre, P., and Hodgkin, T. (2013). The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. *Int. J. Agric. sustainability* 11, 95–107. doi: 10.1080/14735903.2012.691221

Montalba, R., Fonseca, F., Vieli, L., Garcia, M., and Altieri, M. A. (2015). Determinación de los niveles de riesgo socioecológico ante sequías en sistemas agrícolas campesinos de la Araucanía Chilena. Influencia de la diversidad cultural y la agrobiodiversidad. *Papers* 100, 207–224. doi: 10.5565/rev/papers.2168

Morison, J. I. L., Baker, N. R., Mullineaux, P. M., and Davies, W. J. (2008). Improving water use in crop production. *Philos. Trans. R Soc. B* 363, 639–658. doi: 10.1098/rstb.2007.2175

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *Proc. Natl. Acad. Sci.* 104, 19680–19685. doi: 10.1073/pnas.0701855104

Natarajan, M., and Willey, R. W. (1986). The effects of water stress on yield advantages of intercropping systems. *Field Crops Res.* 13, 117–131. doi: 10.1016/0378-4290(86)90015-8

National Research Council (NRC) (1972). *Genetic vulnerability of major crops* (Washington: National Academies of Science).

Perfecto, I., Hajian-Forooshani, Z., Iverson, A., Irizarry, A. D., Lugo-Perez, J., Medina, N., et al. (2019). Response of coffee farms to hurricane Maria: resistance and resilience from an extreme climatic event. *Sci. Rep.* 9, 15668. doi: 10.1038/s41598-019-51416-1

Renwick, L. L., Deen, W., Silva, L., Gilbert, M. E., Maxwell, T., Bowles, T. M., et al. (2021). Long-term crop rotation diversification enhances maize drought resistance through soil organic matter. *Environ. Res. Lett.* 16, 084067. doi: 10.1088/1748-9326/ac1468

Robinson, R. A., and Wallace, R. (1996). Return to resistance: breeding crops to reduce pesticide dependence. *Australas. Plant Pathol.* 25, 216–217. doi: 10.1046/j.1365-3059.1998.00294.x

Schomberg, H. H., White, K. E., Thompson, A. I., Bagley, G. A., Burke, A., Garst, G., et al. (2023). “Interseeded cover crop mixtures influence soil water storage during the corn phase of corn-soybean-wheat no-till cropping systems,” in *Agricultural Water Management*, vol. 278. (Amsterdam, The Netherlands: Elsevier).

Seleiman, M. F., Al-Suhaibani, N., Ali, N., Akmal, M., Alotaibi, M., Refay, Y., et al. (2021). Drought stress impacts on plants and different approaches to alleviate its adverse effects. *Plants* 10, 259. doi: 10.3390/plants10020259

Sharma, R., and Bhardwaj, S. (2017). Effect of mulching on soil and water conservation-A review. *Agric. Rev.* 38, 311–315. doi: 10.18805/ag.R-1732

Sinclair, F., Wezel, A., Mbow, C., Chomba, S., Robiglio, V., and Harrison, R. (2019). *The contribution of agroecological approaches to realizing climate-resilient agriculture* (Rotterdam, The Netherlands: GCA).

Tyagi, V., Nagargade, M., and Singh, R. K. (2020). "Agronomic interventions for drought management in crops," in *New frontiers in stress management for durable agriculture.* (eds. A. Rakshit, H. Singh, A. Singh, U. Singh and L. Fraceto). pp. 461–476, (Singapore: Springer), 461–476.

Vázquez, L. L. (2021). Resilience of agricultural production systems exposed to hurricane Irma in Cuba. *Pastos y Forrajes* 44, 1–14, eI13, 2. Available online at: http://scielo.sld.cu/scielo.php?script=sci_abstract&pid=S0864-03942021000100013&lng=en&nrm=iso&tlng=en.

Vázquez, L. L., Alfonso, J., Matienzo, Y., Elizondo, A. I., González, D., González, R. C., et al. (2015). Vulnerabilidad a la sequía y prácticas adaptativas innovadoras en territorios agrícolas de Cuba. *Agricultura Orgánica* 21, 26–34.

Vázquez, L. L., Aymerich, Y., Díaz, A., Peña, A., Cobas, R., Álvarez, E., et al. (2016). *Resiliencia a sequia sobre bases agroecológicas. Sistematización de un proceso de coinnovación participativa, provincia de Guantánamo, Cuba* (Guantánamo: Editado por: OXFAM, Gobierno Belga, CITMA, ANAP), 145p.

Vázquez, L. L., Castellanos, A., and Leiva, V. (2019). Transición agroecológica y resiliencia socioecológica a sequías en Cuba. *Celia Boletín Científico* 3, 1–43.

Zaongo, C. G. L., Wendt, C. W., Lascano, R. J., and Juo, A. S. R. (1997). Interactions of water, mulch and nitrogen on sorghum in Niger. *Plant Soil* 197, 119–126. doi: 10.1023/A:1004244109990