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Abstract
Fostering sustainable agricultural systems in an era of anthropogenically induced climate change requires the integration of established and emerging frameworks for understanding ecological and evolutionary processes, as well as their implications for resilience and risk mitigation. In this perspective article, we focus on the ecological production unit (i.e., the agroecosystem) and discuss management tactics that could increase resilience to the perturbations associated with climate change. First, we introduce three broad conceptual frameworks to contextualize both agriculture and the impacts of climate change: eco-evolutionary dynamics, ecological disturbance, and resilience and vulnerability. Each framework provides unique insights into why certain types of agroecosystems and agricultural management practices either ameliorate or exacerbate the negative impacts of climate change. Then, we complement these perspectives with a discussion of how risk analysis can be used to assess an agroecosystem's vulnerability to climate-induced perturbations, thereby illuminating opportunities for enhancing resilience. Finally, we discuss the importance of incorporating these perspectives in the design of food systems capable of coping with the challenges posed by a changing climate. Despite the inherent complexity of agroecosystems, the complementary frameworks presented here help point to strategies to enhance resilience to the many challenges posed by climate change, a required step to safeguard global food security and human well-being.

Keywords Climate change, Eco-evolutionary dynamics, Agroecosystem perturbations, Ecological disturbances, Resilience, Risk assessment

1 Introduction

Agriculture and climate are intricately linked. While agriculture is arguably one of the most climate-dependent human activities, it has also shaped the climate since the earliest days of domestication through land clearing, deforestation, land use change, and the emissions of potent greenhouse gases [1]. This linkage, coupled with an ever-growing human population and changing consumer demands, underscores the significant challenge that anthropogenically induced climate change (henceforth, climate change) poses for food systems tasked with producing, processing, and distributing enough food to secure human and environmental well-being.

In many ways, a region's agriculture directly reflects its climate. The long-term patterns of temperature, precipitation, prevailing winds, killing frosts, etc., largely determine the types of crops that can be grown and the methods used to produce them. Although climate primarily influences crop selection and management, weather, i.e., the state of the atmosphere at a given place and time, plays a major role in the success or failure of those crops in any given growing season. In turn, specific management interventions, such as irrigation, fertilization, and pest control, are often used to overcome weather-related constraints on agricultural production.

Alterations in weather patterns and phenomena can be categorized in different dimensions, including the type of event (e.g., flood, drought, frost, etc.), the frequency of occurrence (e.g., monthly, annually, every 100- or 500-yrs, etc.), as well as the intensity, duration, and spatial extent. Climate change influences all these dimensions, thereby directly or indirectly impacting agricultural production in a multitude of ways [2–4]. The ability of an agroecosystem to cope with such perturbations and adapt to new climate conditions is, in turn, strongly influenced by numerous variables, including the crops that are grown and their genetic diversity, the associated beneficial and pest organisms and their genetic diversity, the management tactics that are implemented, edaphic factors, the characteristics of the larger landscape, and the farmers' responsive capacity, to name but a few [5].

Previous work has focused on the social drivers and tradeoffs occurring within these coupled socio-ecological systems, providing a comprehensive synthesis of resilience and vulnerability of food systems to climate change [6, 7]. More recently [8], emphasized the importance of agricultural production as a driver of climate change and explored approaches to understand its interconnections with food systems and human health. Despite these advances, critical questions remain unanswered. Can understanding ecological and evolutionary processes facilitate the development of agroecosystems that are more resilient to the perturbations associated with climate change? What ecological factors influence the risk of disruption to food, fiber, and bioenergy production? Can cropping systems be adapted to mitigate the impact of such perturbations? If so, what principles and practices can we apply to ensure that food systems remain viable in a changing climate? Answering these questions represents a daunting task.

In this perspective article, we explore these questions by delving into three established and emerging ecological and evolutionary frameworks that we believe provide useful conceptual models for further understanding and addressing the challenges climate change poses for agricultural production. To synthesize the insights this perspective provides, we then apply the well-established tools of quantitative risk analysis to assess an agroecosystem's vulnerability to the impacts of climate change, thereby illuminating opportunities for enhancing resilience. Finally, we integrate these ecological and evolutionary concepts with a food system perspective, a necessary next step if we are to successfully meet the challenges posed by a changing climate.

2 Framework #1: eco-evolutionary dynamics

Agroecological practices such as diversifying cropping systems, cover cropping, and reducing tillage can enhance the resilience of an agroecosystem [9]. Yet, by altering both short- and longer-term temperature and precipitation patterns, climate change can create ecological mismatches between crops, the associated biodiversity (e.g., all organisms other than crops, including pests, beneficials, and neutral species), and the biogeochemical and physical processes that regulate their growth, phenology, reproduction, and interactions [10, 11]. In extreme cases, such as severe and prolonged drought, such mismatches may limit an agroecosystem's ability to function [12]. While evidence of climate change-induced mismatches continues to emerge [13], their long-term implications for crop performance, survival, and fitness of the associated biodiversity, as well as its adaptive evolution, phenotypic plasticity, and gene flow remain unclear. An eco-evolutionary framework can help us understand these mismatches and design management practices to mitigate and adapt to climate change's impact on agricultural production.

As a relatively new discipline, eco-evolution is an integrative field that examines how mutually dependent ecological and evolutionary dynamics emerge from natural selection, habitat distribution, and propagule dispersal [14, 15]. In essence, eco-evolution evaluates the reciprocal feedback that occurs between ecological and evolutionary processes. The impacts of eco-evolution have been observed in numerous biological processes, including intra- and inter-specific interactions such as host-pathogen [16], predator-prey [17], and competition [18].

Traditionally, agronomists have worked under the assumption that evolution occurs over temporal scales too long (i.e., centuries to millennia) to influence organisms over time scales that are agronomically and ecologically relevant (i.e., days to years). Yet, there is a growing body of theoretical and empirical evidence that ecological and evolutionary timescales overlap and that eco-evolutionary dynamics shape processes occurring from the individual to the ecosystem level [19]. In agroecosystems, eco-evolutionary processes arise as the associated biodiversity evolves in response to management, biological, and environmental selection pressures. Agroecologists and evolutionary biologists have used eco-evolutionary concepts to explore changes in insect-plant and plant-microbiome interactions, the provision of ecosystem services, pest dynamics, and the evolution and management of pesticide resistance [19–22].

Over the short term, plant breeding can buffer the impact of climate change on agricultural production [23]. However, the responses of the associated biodiversity to climate change depend on the genetic variability within the respective populations, the rate of migration and extinction, and the disturbance regime, making it more difficult to assess the outcome of eco-evolutionary processes. Yet, in the face of climate change, it is plausible to predict the emergence of novel mismatches between newly developed crop varieties, the associated biodiversity, and their environment [11]. For example, an 8-year field survey observed that extreme high temperatures differently impacted evolutionary and plastic changes across two worldwide distributed cereal aphid species (*Rhopalosiphum padi* and *Sitobion avenae*), resulting in a shift in species dominance [24]. Given their roles as crop disease vectors, shifts in the dominance of these species could have important implications for plant-pathogen interactions as well as breeding programs targeting disease resistance [25]. Additionally, the evolution of herbicide resistance coupled with unprecedented climate conditions creates emerging weed management challenges due to novel biological interactions, technical challenges, and shifts in species composition [26]. These new challenges will likely be conditioned by the identity of crop and weed species involved because the individual and combined effects of elevated atmospheric carbon dioxide (CO_2), drought, or warming on competition vary as a function of the photosynthetic pathways of the weed/crop pair and on crop identity [27].

Ecological disturbance provides a complementary framework for contextualizing agriculture, the impacts of climate change, and resulting eco-evolutionary mismatches. This framework, in turn, can inform and assist farmers in decision-making, which could result in more resilient agroecosystems. The following section explores these concepts.

3 Framework #2: ecological disturbance

An ecological disturbance can be defined as "*A cause; a physical force, agent, or process, either abiotic or biotic, causing a perturbation… in an ecological component or system; relative to a specified reference state and system; defined by specific characteristics*" [28]. In this chapter, following [29], we define perturbations as fast-occurring changes to a system's equilibrium resulting from a disturbance event. Perturbations usually originate outside the system, such as erosion due to extreme weather events, but may also result from internal processes, including pest outbreaks and fires.

Disturbances and perturbations are integral features of all ecological systems, including agroecosystems. What distinguishes agroecosystems from natural and semi-natural ecosystems, however, is their high dependency on human-mediated disturbances to achieve specific management goals. Indeed, agricultural activities such as preparing the soil, seeding, grazing, applying fertilizer, managing pests, and harvesting crops can be categorized as internal disturbances. On the other hand, agroecological tactics such as increasing cropping system diversity, agroforestry, no-till planting, and mulching are commonly used to reduce and mitigate perturbations [10].

Disturbances inherent to agriculture (i.e., *internal* disturbances) interact with disturbances that are *external* to the agroecosystem (i.e., weather-related disturbances). Climate change alters these interactions, potentially amplifying the characteristics and magnitudes of the resulting perturbations. For example, changes in moisture and temperature conditions interact with management practices in determining shifts in soil microbial [30] and weed communities [31], and result in an overall decrease in crop production [32]. Also, predicted atmospheric CO_2 levels could result in faster crop growth, but these beneficial effects are expected to be offset by increased temperatures and altered patterns of precipitation [33], as well as shifts in multitrophic interactions, pest pressure, and efficacy of management tactics [34, 35].

The timing of these climate-induced disturbances relative to crop production could condition the magnitude of the perturbations and the associated crop and management responses (Table 1). While a mature stand of perennial forages may be less impacted by a relative lack of snow cover, such disturbance can impact a recently planted cool-season perennial forage stand, resulting in crop damage due to overwintering injury [36, 37]. Also, early or excessive warming, drought, or flooding can disrupt an agroecosystem by altering the planting and harvesting schedules of crops, reducing the number of working days, or decreasing the efficacy of pesticide applications and pest management practices. In the short term, the outcomes of these interactions determine yields and may lead to more intense perturbations, such as new management practices that occur at different

Table 1 Examples of perturbations arising from the interaction between disturbances inherent to agriculture (internal) and environmental disturbances exacerbated by climate change (external)

Internal disturbance (inherent to agriculture)	External disturbance (exacerbated by climate change)	Perturbation (result of the interaction between internal and external disturbances)
Soil tillage	Extreme rainfall event	Soil erosion by water, leaching of nutrients and/or pesticides
	Extreme wind	Soil erosion by wind, loss of nutrients and/or herbicides
	Drought	Soil erosion by wind, aerial transport of nutrients and/or pesticides, increased soil salinity
Planting	Extreme rainfall event	Soil erosion, seed movement, seedling mortality if germinated, increase in pathogens and other pest organisms
	Extreme wind	Soil erosion, crop injury, loss of pesticides
	Drought	Soil erosion, seedling death if germinated, increased soil salinity
	Early or late killing frost	Crop death or reduction in productivity depending on timing/physiological stage
	Lack of insulation by snow cover	Crop death or reduction in productivity depending on timing/physiological stage, frost-heaving of soil and root damage
Pest management	Extreme rainfall event	Delayed control, reduced efficacy, increased crop damage, soil erosion depending on control method
	Drought	Increased pest damage, reduced efficacy
	New pest complexes	Increased damage due to lack of management options
Crop development and harvest	Extreme rainfall event	Minimal
	Drought	Crop damage and reduced yield, or persistence, if perennial
	Hail	Crop damage and reduced yield

Perturbation refers to a fast-occurring change to a system's equilibrium resulting from a disturbance event. In these scenarios, we assume the internal disturbance precedes the external disturbance

times, for longer durations than normal, or that may even be entirely new for the system [38, 39]. These disturbances represent novel eco-evolutionary pressures that create new ecological mismatches, modifying the interactions between crops and the associated biodiversity.

There are four discrete types of disturbances [40]: destruction, discomposition, interference, and suppression. Destruction disturbances reduce or destroy biomass, potentially damaging or killing individuals. In agriculture, these are arguably the most important types of internal disturbances, encompassing nearly every aspect of crop production. In general, the frequency and intensity of internal destructive disturbances are highest in annual cropping systems compared to perennial ones, such as livestock production, pasture-based systems, tree crops/orchards, and agroforestry systems [41, 42]. While the nature and magnitude of perturbations arising from destruction disturbances can be exacerbated by climate change, further increasing the magnitude of ecological mismatches described above, their impact will depend on when they occur, as well as the resilience of the cropping system. For example, an extreme precipitation event immediately following major tillage will likely result in more severe soil erosion and nutrient loss than one after the crop canopy has closed, or one in a mature pasture or orchard system.

Discomposition disturbances alter the density of populations within a community and include eliminating or adding specific populations to the system [40]. Discomposition disturbances are also inherent to agriculture, with crop breeding and selection, introduction of agricultural livestock, promotion of beneficial organisms, and species-selective pest control practices being the most obvious examples. Warmer temperatures can modify pest reproductive cycles, facilitate their movement, or promote the dispersal of novel pests that can decimate entire crops or affect crop safety [26, 39, 43, 44]. Notably, higher temperatures have resulted in an expansion of the geographic range of insect pests and changes in their interaction with host plants and natural enemies, as well as increases in both overwintering survival and the number of generations per growing season [45]. Changes in the onset or duration of the growing season can also result in additional discomposition disturbances. For example, the lengthening of shoulder seasons due to climate warming can lead to mismatches between crop phenology, the timing of pest outbreaks, and the dynamics of beneficial organisms such as parasitoids and generalist predators [45, 46]. This desynchronization of insect pests and their natural enemies (i.e., ecological mismatch) could impact farm economic sustainability, as reductions in biological control services would require concomitant investments in economically and environmentally costly alternative crop protection measures [47].

The third type, interference disturbances, are those that inhibit the flows and exchanges of energy, matter, or information between components of an ecosystem [40]. Irrigation, fertilization, or the application of other amendments or materials represent examples of this type of disturbance in agroecosystems. Depending on their timing and duration of occurrence, climate-induced disturbances such as drought, extreme rainfall, or excessive heat can increase ecological mismatches by altering the cycling and availability of soil nutrients from fertilizers and the mineralization of soil organic matter [48]. The resulting perturbations to the agroecosystem include nutrient loss via leaching, emissions of greenhouse gases, and immobilization of nutrients such as phosphorus, which may result in long-term declines in soil fertility [49].

The final type of disturbance, suppression disturbances, occurs when the "normal" disturbance regimes necessary for maintaining ecosystem functioning are altered or prevented [40]. Any phenomena that interfere with the normal regime of disturbances necessary to achieve the production objectives of an agroecosystem, including weather events or changes in longer-term weather patterns, could be considered a suppression disturbance. For example, drought stress or hurricanes are phenomena that occur more frequently due to changing climates and force smallholder farmers to select new crops and redesign their farming systems, with highly diversified farms being less damaged by suppression disturbances [10]. Similarly, in conventional systems, the decreased efficacy or enhanced volatility of certain herbicides under extreme heat could be considered a disturbance [35]. The inability of a farmer to conduct a timely application of a pesticide, perform secondary tillage, or harvest a crop because of wet soils due to excessive rainfall is another example of how climate change can suppress the "normal" agricultural disturbance regime [50].

In any given agroecosystem, how disturbances interact depends on their nature, magnitude, frequency, scale, and timing relative to one another. Farmers, as managers of the internal disturbance regime, have, to some degree, the ability to influence these interactions and, therefore, the resilience and vulnerability of agroecosystems to predicted climatic conditions.

4 Framework #3: resilience and vulnerability

Proposed more than fifty years ago to evaluate how systems respond to perturbations [51], a resilience framework has since been used to assess socio-ecological systems, including agroecosystems [9, 10, 52, 53]. In essence, resilience is characterized by a system's ability to adjust to new conditions (i.e., adaptive capacity), moderate the associated damages and consequences, and take advantage of potential opportunities in the face of unprecedented scenarios [54–56]. Four parameters define a given system's behavior after being exposed to an internal or external disturbance and can help us design climate-resilient agroecosystems [57]: (1) robustness or resistance is the capacity to withstand a disturbance before a significant change occurs, (2) redundancy denotes the extent to which elements of the system are replaceable, (3) recovery indicates the extent to which a system rebounds to a desirable state after a disturbance, and (4) reorientation refers to the practices that enable alternative system outcomes following disruptions.

Within agroecosystems, resilience to climate change refers to the system's capacity to sustain sufficient and nutritious food production, supply, and access in the face of weather-induced perturbations. However, as complex socio-ecological systems, agroecosystems have multiple components and processes, and the degree of resilience may arise through asynchrony or conflicts among them [58]. For instance, drought conditions decrease crop yield [59] but can also result in limited weed abundance and growth [60]. Also, increased CO_2 may enhance crop growth, but its overall impact on crop-weed competitive interactions is mediated by species identity, moisture availability, and temperature conditions [27]. Despite these limitations, management activities and system diversification practices that take place at the field, farm, and landscape levels can increase the overall resilience of agroecosystems [53] (Table 2).

An ecosystem's homeostasis (i.e., its capacity to maintain a stable equilibrium, even when external conditions change) is strongly determined by its successional maturity, which, in turn, is determined by both the frequency and intensity of disturbance events (sensu [61]). Hence, the ecological networks and attendant processes that contribute to the functioning of ecosystems are comparatively less developed, i.e., "less mature," in agroecosystems where internal processes have been replaced with off-farm inputs that maintain the system in a perpetual state of initial early secondary succession [41, 61]. Consequently, an external disturbance induced by climate change may be highly impactful in agroecosystems where the ecological networks and redundancies that might ameliorate the perturbation are either "immature" or non-existent, while the impacts may be greatly reduced or nonexistent in more successionally mature systems, such as diversified agroforestry systems [62]. Agroecological tactics such as reduced tillage intensity and cropping system diversification can lessen the impact of drought on soil structure, water infiltration and conservation, erosion rates, and crop yields [63–65], illustrating how management practices can modify resilience even in otherwise "less mature" agroecosystems.

Table 2 Examples of field-, farm-, and landscape-level management practices that can enhance agroecosystem resilience to climate-induced disturbances

Field scale	Farm scale	Landscape scale
Use of stress-tolerant varieties	Cropping system diversification	Landscape diversification
Cover cropping	Adaptive management	Maintenance of refuge habitats for beneficial organisms
Soil health improvement through green manures and organic residues	Crop and livestock integration	Promotion of the associated biodiversity
Promotion of the associated biodiversity	Promotion of the associated biodiversity	
Replacement of off-farm inputs with ecologically based processes	Agroforestry	

Because an agroecosystem's susceptibility to climate change is determined, to some degree, by the frequency and intensity of its internal disturbances (*see Framework #2: Ecological disturbance*), it may be possible to qualitatively assess its relative vulnerability to climate change (Fig. 1). To make such an approach quantitative, one would need to develop metrics for quantifying the intensity of agricultural disturbances, similar to the approach developed to assess soil disturbances associated with tillage [66, 67]. Future research in this area could prove useful.

Contextualizing agriculture and climate change within a resilience framework can be used to explain the degree to which disturbances inherent to an agroecosystem may

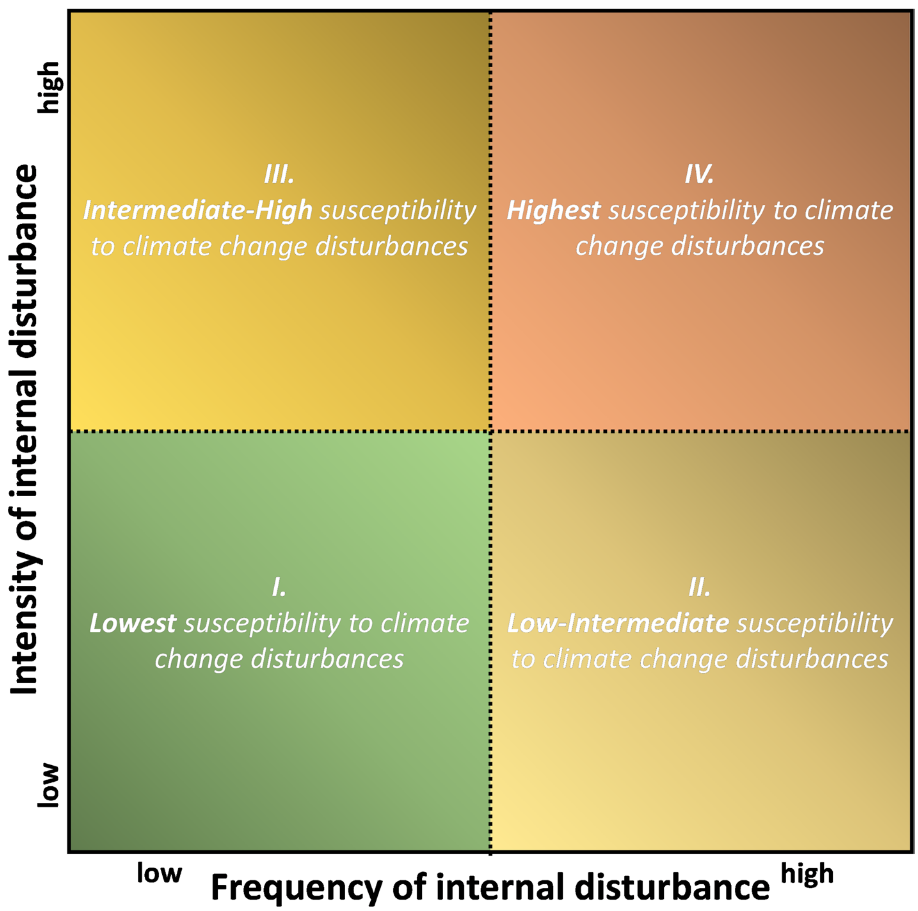

Fig. 1 Conceptual model illustrating the interactive roles of internal agricultural disturbance frequency and intensity in determining an agroecosystem's susceptibility to perturbation from climate change disturbances. Internal disturbances are inherent to agriculture (e.g., soil tillage, planting, pest management, and harvest). Agroecosystems in quadrant IV are managed through frequent and intensive internal disturbance, which makes them highly susceptible to climate change-driven perturbation (e.g., rainfed annual row crop and vegetable production systems). Compared to quadrant IV, agroecosystems in quadrant III (e.g., perennial bioenergy systems, tree crops, and orchard systems) are relatively less susceptible to perturbations arising due to climate change disturbances, and the impacts will be strongly dependent on the timing of the external and internal disturbance events relative to one another. An agroecosystem managed with low intensity but frequent disturbance (quadrant II), such as perennial forages and pastures, would also be less susceptible to perturbation than quadrant IV systems because it would likely feature well-developed crop canopies and root and soil systems that would impart resilience against some types of external climate change-driven disturbances. The least susceptible agroecosystems (quadrant I) would be those managed with minimal internal disturbance (e.g., multi-strata agroforestry systems) and would feature characteristics of later successional ecosystems, including high levels of organismal and structural diversity, perennial life history strategies, and well-developed ecological networks. Imparting these characteristics within any given agroecosystem, even annual row crops, by reducing either internal disturbance frequency or intensity would likely shift the agroecosystem toward a state of decreased relative susceptibility

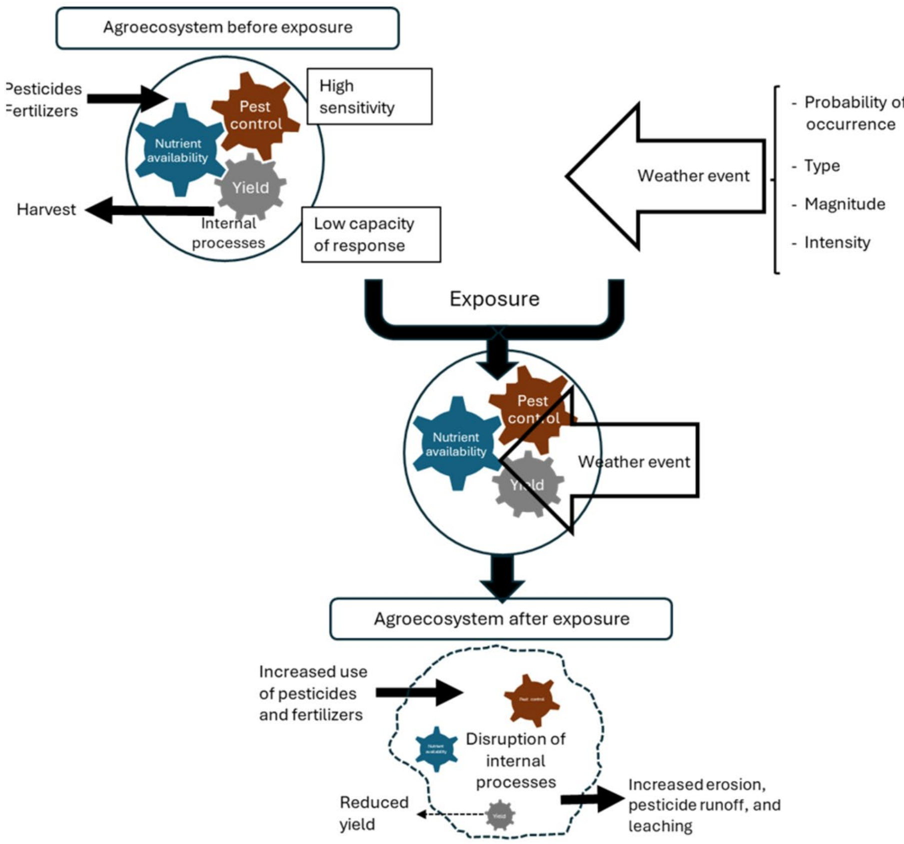

Fig. 2 Example of the relationships between the threat of perturbation due to an external disturbance, such as an extreme weather event, and the vulnerability and adaptive capacity of a simplified agroecosystem with low inherent diversity and resilience. Only after the agroecosystem is exposed to the disturbance, represented by the overlap between the agroecosystem and the weather event, the internal processes are interrupted, and perturbances can be observed. If this happens, the farmer may need to increase the intensity of internal disturbances (e.g., higher tillage, fertilization, and pesticide use) to restore the system. The vulnerability of the system (i.e., sensitivity and capacity of response) is represented with boxes. Table 2 lists some management practices the farmer can apply at the field, farm, and landscape level to enhance agroecosystem resilience to climate-induced disturbances. Adapted from [29].

determine its vulnerability to climate change. Following [29], we define the vulnerability of a system as its potential for change when confronted with an external perturbation, rather than the actual outcome of such confrontation. The vulnerability of an agroecosystem is negatively related to its degree of resilience, and it can be estimated through parameters such as loss of biodiversity, soil fertility, or productivity. After the agroecosystem is exposed to a disturbance, its internal processes are interrupted, and perturbations can be observed (Fig. 2).

Farmers can implement management practices that may reduce an agroecosystem's vulnerability to climate-induced perturbations. Increasing biological, management, and landscape diversity is a central tenet to achieve this goal. Diversified farming systems may contain sufficient functional diversity across genetic, species, field, farm, and landscape scales to secure the ecological networks and processes required to minimize an agroecosystem's vulnerability to climate change [68, 69]. For example, a review of 172 reports and case studies of traditional agroecosystems from Africa, Central and South America, Asia, and the Pacific indicate that tactics such as the adoption of stress-tolerant species, sustainable use of natural resources, agroforestry, crop improvement, and system diversification, among others, increase agroecosystem resilience [70]. Similarly [9], presents numerous examples in which enhancing farming-system diversity reduces its vulnerability to unprecedented or extreme weather conditions induced by climate change. After Hurricane Mitch devastated large parts of Nicaragua in 1998 [71], farms that included sustainable practices such as contour plowing, cover cropping, intercropping, and use of agroforestry were less impacted than conventional farms that plowed with the slope and used external chemical inputs.

In the context of climate change, an increase in the adaptive capacity of an agroecosystem comprises actions that occur mostly within a cropping system and are aimed at coping with climate-induced disturbances. Incremental modifications such as shifting planting dates, breeding crop varieties to be heat- or drought-tolerant or improving irrigation may moderately improve the adaptive capacity of a cropping system [72]. However, a more durable increase in agroecosystems' adaptive capacity will result from transformational changes aimed at redesigning agroecosystems by shifting away from monocultures and their high dependence on off-farm inputs [69]. Examples of such actions include increasing cropping system diversification, enhancing soil-water retention, integrating crop-livestock enterprises, adopting agroforestry systems, enhancing biodiversity, and improving integrated pest management. Adaptive capacity can also be enhanced through actions and policies aimed at the origins of these perturbations and stresses (i.e., reducing greenhouse gas emissions). On this point, it is worth noting that increasing attention is being paid to the notion of "maladaptive" agricultural interventions, where practices or policy actions aimed at improving agroecosystem resilience inadvertently favor some types of farming systems (and farmers) over others, thereby maintaining exacerbating socioeconomic inequalities that may already exist [73].

5 Assessing climate risks in agriculture

Now that we have considered three distinct frameworks for qualitatively contextualizing the climate change problem in agriculture, we need to qualitatively and quantitatively assess climate resilience, and, ideally, develop cropping systems with enhanced resilience. Risk, risk assessment, and risk management are well established concepts in systems analysis, policymaking, and regulation and may provide the tools necessary for quantitatively assessing resilience in agriculture.

The concept of risk, i.e., the probability of occurrence of a usually undesirable event, was recognized as early as 3200 BCE [74]. Compensation insurance for loss began about 1900 BCE, but it was not until the 1600s CE that risk was formally linked to mathematics, specifically probability theory [75]. For ecological risk assessment, risk refers to the joint probability of effect and exposure to a disturbance. Quantitatively, risk can be defined as:

$$\text{Risk } = f\,(\text{effect},\ \text{exposure})$$

The entity producing the effect and exposure is often referred to as a hazard or stressor [76, 77]. Hazard also refers to the inherent ability of a substance, organism, or activity to cause harm. Effect is the positive and/or negative consequences produced by the hazard, and exposure refers to the frequency of an interaction of the hazard with a receptor.

In the context of climate change, external climate-related disturbances can cause harm in the form of physiological stress on a crop, modifying pest pressure, or impeding management practices, and the consequences can be observed at the ecosystem level (see *Framework #2: Ecological disturbance*). The frequency of climate-induced stress relates directly to exposure. Therefore, we can mathematically estimate climate-induced risk to the agroecosystem by considering both effect and exposure.

Changes in agricultural practices, such as releasing crop varieties tolerant to environmental and biological stressors, may not reduce climate-induced stress. However, by increasing the crop's tolerance, these practices would temporarily enhance the system's resilience to climate-induced stress [78]. Therefore, the risk is reduced, and successful adaptation is temporarily achieved (see *Framework #3: Resilience and vulnerability*). In the long-term, a redesign of agroecosystems to include polycultures, agroforestry systems, and crop-livestock mixed systems based on ecologically driven nutrient management, pest management, and water conservation policies could help increase overall agricultural resilience in the face of climate change [9, 70]. Moreover, these tactics can be quantified within a risk analysis paradigm to determine if risk is lowered.

Risk analysis can help us improve agroecosystem management decisions in the context of climate change. Briefly, risk analysis is the assessment, management, and communication of risk [70–80]. The assessment of risk flows logically through the well-defined steps of (1) problem formulation, (2) effect identification, (3) effect-response relationships, (4) exposure assessment, and (5) risk characterization. The stepwise nature of risk assessment is a process whereby risk issues can be presented, compared, and considered [81–83]. It is an established, robust, and science-based tool for evidence-based decision-making [75]. Risk analysis, then, is risk assessment with additional sociological elements such as public opinion, legislation, and regulatory decisions. When these elements occur in a democratic society, risk management happens [75].

As it relates to climate change and agroecosystem management, risk analysis allows for a systematic, quantitative evaluation of strategies that reduce climate-induced ecological mismatches (see *Framework #1: Eco-evolutionary dynamics*) and enhance agroecosystem resilience. For example, in increasingly drought-prone agroecosystems, risk may be mitigated by adopting no-tillage in combination with mulching during a fallow period. This agroecological approach increases precipitation storage efficiency, soil-water storage, water-use efficiency, and crop yield [84]. However, no-till fallow may introduce other risks, such as increased disease and other pest incidence, increased wind and water erosion where there is no plant cover, yield variability, modified solar insolation, and selection of herbicide resistant weed biotypes [21, 85, 86]. Risk analysis can provide an important formal framework to compare all risks and management strategies using well-established and defined terms and metrics [75, 87]. This ability enhances predictive power within highly complex nested systems that include climate, agroecosystems, food systems, and other social systems.

In the context of climate change [9], proposed a risk framework to evaluate agricultural resilience:

$$\text{Risk} = (\text{Threat} * \text{Vulnerability}) \div \text{Response Capacity},$$

where Risk refers to any natural phenomenon, such as drought, hurricane, or flood that will result in a change in the environment, and Threat measures the climatic event's intensity, frequency, duration, and impact (i.e., yield losses due to storm or drought). As defined above (see *Framework #3: Resilience and vulnerability*), Vulnerability is the system's potential for change when confronted with a perturbation and is determined by the agroecosystem's biophysical and socio-economic conditions that enhance or reduce its exposure to the threat. Finally, Response Capacity is the potential of the agroecosystems to resist and recover from the threat (i.e., ecosystem resilience), and it is conditioned by the ecological features of the farms and management strategies.

The formula of [9] is similar to the longstanding definition of risk presented above: Risk = f(effect, exposure). According to [9], for a climate event to be considered a risk depends on whether there is an agroecosystem vulnerable to it, the climate event's magnitude, and the farmer's capacity to reduce risks. Vulnerability is essentially an element of Exposure and considers the agroecosystem's internal processes. Threat in [9] is equivalent to Effect, although it includes elements of Exposure because it also refers to frequency and intensity. Whereas we discuss reducing risk by altering effect, exposure, or both [9], introduces a denominator, Response Capacity, that is equivalent to altering effect and exposure.

Regardless of the formula used to assess the risk of an agroecosystem to climate-induced disturbances, we argue that risk and risk analysis are valuable tools when evaluating a system's vulnerability, adaptive capacity, and resilience strategies across agricultural, socioeconomic, and ecological scales.

6 Conclusions: increasing resilience from crop fields to food systems

Agroecosystems are characterized by multiple, complex, and non-linear dynamics; hence, the predictability of their responses to stressors such as climate change is limited, especially as they are shaped by both environmental and human factors [88]. This, in turn, creates major threats to the larger-scale production, processing, and distribution of agricultural products, i.e., the food system. Given this dependency, the eco-evolutionary, disturbance, resilience, and risk analysis frameworks we discussed to this point, primarily in the context of the production unit, will ultimately be of limited value to enhancing human wellbeing unless they also contribute to an improved understanding of the factors that mediate socio-ecological tradeoffs and vulnerabilities of food systems.

In the short-term, responses at the agroecosystem level to climate change may involve technological fixes such as developing drought-resistant crop varieties, improved pesticides, and precision agriculture techniques. However, transformational changes aimed at shifting away from monocultures and increasing reliance on internal ecologically based processes are essential to increasing agroecosystem resilience to climate change [89]. Despite this, the adoption of climate-resilient agricultural practices has been constrained by socio-political and economic factors, hindering producers' adoption of alternative cropping systems [90]. Addressing these constraints requires the participation of multiple food system stakeholders to promote policies and regulations that allow agricultural producers to adopt climate-resilient practices and diversify their production portfolio.

Concerns about the degree of agroecosystem vulnerability to climate change, and the solutions to address this problem, vary depending on the stakeholders' worldviews, production region, and occupation [91, 92]. These disagreements may, in turn, affect the development of comprehensive policies and management strategies to modify a food system's adaptive capacity. To be climate-resilient, at the food system level, any such strategies must also consider the potential for maintaining or exacerbating existing socio-economic inequalities and/or vulnerabilities within farming communities [73].

We acknowledge that much of our focus has been aimed at the field and agroecosystem level, and primarily in the context of the temperate northern hemisphere. However, climate change extends beyond the boundaries of individual farms, impacting ecosystems and processes at much larger scale [93]. Even if the farm boundary is the primary unit under farmer-control, many of the ecological processes we highlighted as supporting on-farm resilience (e.g., soil moisture retention and cycling, predator-prey dynamics) function at broader landscape scales. Indeed, in many cases landscape-level dynamics may outweigh the influence of on-farm practices. For example, over-extraction of groundwater for irrigation and other domestic and industrial uses (e.g., cooling AI processing facilities) can lower aquifer levels to the extent that on-farm management strategies are unable to compensate. While transformational change is required at the farm-scale [89], so too it is required at the landscape- and societal-level. Useful evidence and frameworks in this regard can be found in several sources [94, 95]. How to manage these landscape-level dynamics, given the complexity of the agro- and socio-ecological systems involved, remains an open question [96].

It is also important to consider that food production is the primary global driver of land cover and land-use change, and among the most severe greenhouse gas emitters [8]. Globally, the complexity and interconnectedness of agroecosystem production, climate change, and food systems demand for recognizing that its effects are often most severe in regions that contribute least to its causes [97]. For example, greenhouse gas emissions from industrial and agricultural activities in the Global North can lead to more frequent disasters in the Global South, like hurricanes in the Caribbean [98]. Although climate change impacts regions in diverse ways; its cumulative effects are increasingly challenging the agricultural sector and broader food system globally [99]. Thus, a food system resilient to climate change, i.e., one that provides consistent, nutritious food despite climate-induced and other perturbations, must be a global one [89, 100]. The ecological principles that support the resilience of a system remain the same: withstand, recover from, and adapt to disturbances and enable alternative system outcomes following disruptions [57].

Understanding the ecological and evolutionary processes related to climate change, managing disturbances, and assessing risks at all relevant scales are necessary steps. This understanding must ultimately lead to integrated planning approaches that can help overcome isolated sector- or nation-limited strategies and policies [99]. Integrated planning requires the consideration of multiple stakeholders, which inherently conflict with top-down governance structures. Instead, it calls for polycentric governance, a decentralized multi-stakeholder system adaptive to local conditions. Thanks to its learning-oriented, flexible, and pluralistic nature, polycentric governance proves more suitable than the prevailing top-down approach for addressing the complexities of climate transition. This approach would guide the necessary "climate transition," fostering collaborative and adaptive solutions to the challenges posed by climate change [8]. The challenge, thus, is to aim for sustainability while not jeopardizing food security, ensuring, now and in the future, access to abundant, nutritious, affordable, and culturally appropriate food for all humans [89]. Incorporating eco-evolutionary concepts and risk management evaluations of agroecosystem resilience into the analysis of socio-ecological systems could provide powerful tools to unlock socio-political and economic constraints hindering the adoption of food systems resilient to global climate change.

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Author contributions
FM: Conceptualization, writing – conceptualization, investigation, original draft, review, and editing. RE: investigation, methodology, writing, review, and editing. RKDP: investigation, methodology, writing, review, and editing. BJS: investigation, methodology, writing, review, and editing. LSS: investigation, methodology, writing, review, and editing. RGS: investigation, methodology, writing, review, and editing.

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Declarations.

Data availability
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Declarations

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