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FEATURE

Building resilient soils through agroecosystem redesign under fluctuating climatic regimes

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Most current farming systems are designed to meet narrow goals of maximum production and short-term returns, a singular strategy that often leads to unexpected and undesirable emergent environmental consequences, such as loss of biodiversity, damage to the ecosystem, and other diminished ecosystem services. Responsible actions in agricultural practices and system design are needed to reverse this current trend and develop agroecosystems that will enhance resilience under increasing climatic fluctuations. Resilience refers to the ability of an agroecosystem to recover from external and internal stresses and adapt to changing conditions without significantly losing its key functions and services. Developing resilient soils and agroecosystems with "spring-like behavior" or elastic response is a priority in the face of unpredictable and increasing fluctuations of climate. The future can be characterized by conditions of extreme and more frequent droughts, excessive moisture in some areas due to intense rainstorms and flooding events, unexpected heat waves, and unseasonable snowstorms and frigid temperature conditions (Karl et al. 2009).

In the realm of soils, for example, resilient soils should have potential to rapidly dry out when weather is wet, retain available water when weather is dry and hot, and remain warm when weather is cold. Resilient soils are the basic foundation of resilient agroecosystems that should recycle water, carbon (C), and nutrients; maintain clean water and air; and continue to produce food, feed, fuel, and fiber under abrupt fluctuations in climate. Soil resilience is one component of a larger initiative to develop social-ecological resilience in human-managed agroecosystems (Walker et al. 2004). This review provides a perspective on potential options for innovative management strategies that can enhance resilience of soils and agricultural systems under abrupt climatic fluctuations.

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CHALLENGES WITH CURRENT MANAGEMENT SYSTEMS

One major challenge is the specialization in most agricultural systems to primarily produce one or a narrow range of crops or livestock species with essential investment of high levels of imported external inputs. These systems are not designed to deliver multiple ecosystem services. Such services include supporting (i.e., water, C, and nutrient cycling), provisioning (i.e., production of food, fuel, fiber, and feed; and provision of clean water and air), regulating (i.e., regulation of water quality, air quality, and climate change), and cultural (i.e., nonmaterial dimensions such as aesthetic, recreational, and spiritual) services (Millennium Ecosystem Assessment 2005).

Expansion of croplands worldwide has not only degraded and diminished the above ecosystem services but also reduced resilience of soils and agroecosystems. For example, intensive cultivation has, in general, reduced soil C levels, increased risks of nonpoint source pollution (i.e., hypoxia in the Gulf of Mexico), and reduced soil biodiversity as well as wildlife habitat and ecosystem diversity, among others. This decrease in ecosystem services will be further compounded by increasing extreme fluctuations in climate on local and global scales.

Despite the substantial adoption of improved practices such as conservation tillage, there are continuing concerns about nonpoint source pollution, losses of soil C, and decreased soil productivity (Kladivko et al. 2014; Palm et al. 2014). For example, both no-till and conventional tillage practices can contribute to loss of soil C when compared with natural systems (Luo et al. 2010; Powlson et al. 2014). Unresolved questions include the following:

1. How can we restore ecosystem services from agricultural lands?
2. How can we build resilient soils and agroecosystems for an uncertain climate?
3. Are there potentials for redesigning current agricultural landscapes by adopting innovative practices that mimic natural systems and become key contributors to a strategy to increase soil and agroecosystem resilience?

STRATEGIES TO INCREASE RESILIENCE: A SOIL CARBON EXAMPLE

Practices that improve soil resilience can concomitantly improve agroecosystem resilience as soils perform essential processes including recycling and retaining C, water, and nutrients; moderating soil temperature and energy fluxes; filtering and degrading nonpoint source pollutants; providing habitat for diverse soil organisms; and many others that result from interactions among soil biological, chemical, and physical properties.

One valuable example revolves around the many impacts of changes in soil organic C, which are complex and dynamic indicators of soil resilience. A flow chart of cumulative effects of practices as well as feedbacks is presented in figure 1. An increase in soil C enhances soil processes

Figure 1

Abundant aboveground and belowground biomass production increases soil organic carbon (C) and improves other dynamic soil properties enhancing soil and agroecosystem resilience and services.

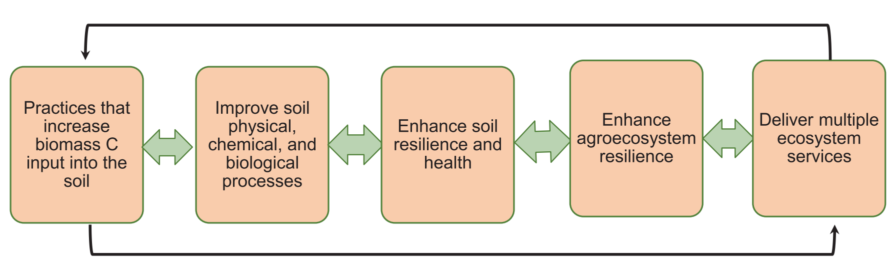
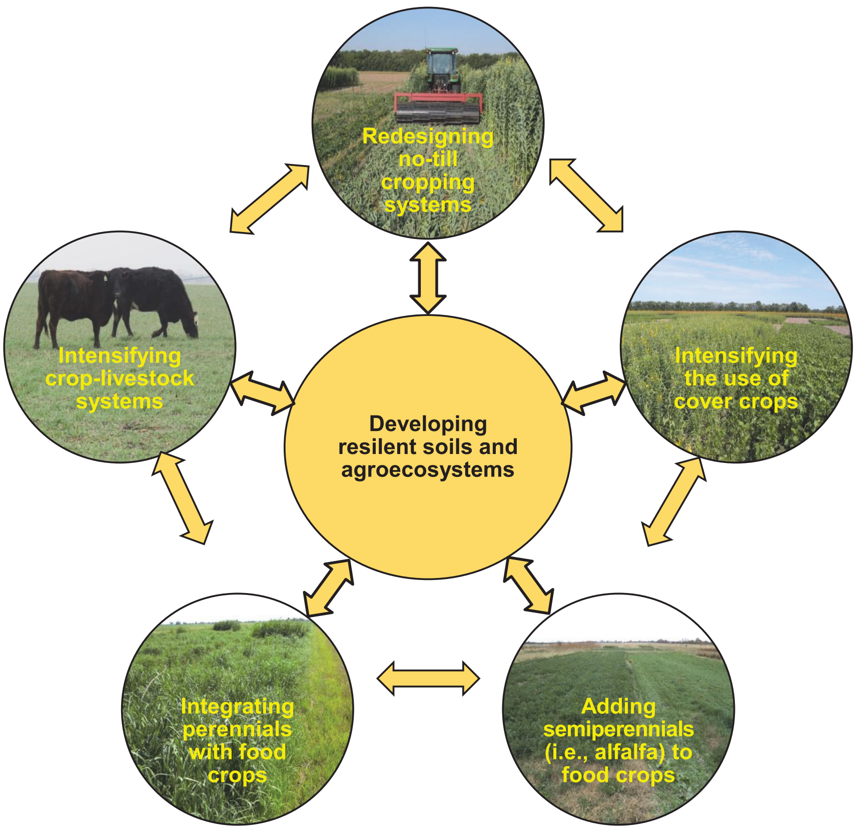


Figure 2

Examples of potential strategies to enhance soil and agroecosystem resilience under increasing climatic fluctuations.



that impart buffering capacity to the whole soil against external and internal stresses. Higher soil C content improves soil physical, chemical, and biological processes. For example, greater levels of soil C increase soil aggregation, reduce susceptibility of the soil to compaction, increase water retention capacity, and help to degrade pollutants (Kladivko et al. 2014; Blanco-Canqui and Benjamin 2013). Soil organic C accumulation can increase the buffering capacity of the soil, thus adding greater resilience to the system.

In contrast to these desirable emergent properties of increasing soil organic C, it is well recognized that soil C in agricultural lands has declined by about 50% since these soils were first brought into production due to intensive cultivation, which resulted in the degradation of soil processes (David et al. 2009). Strategies to halt the continued decline in soil C, to restore lost soil C, and to improve soil processes are needed for enhancing both soil and agroecosystem resilience. Innovative practices that diversify current systems or mimic natural systems and increase soil organic C levels are needed to increase soil and agroecosystem resilience. To achieve this goal, redesigning current agricultural landscapes to include improved management practices is a critical strategy for future food production systems (figure 2).

PRACTICES FOR ENHANCING SOIL AND AGROECOSYSTEM RESILIENCY

Mimicking Nature: Integrating Perennial Plant Species with Food Crops. Integrating perennial plant species with food crops is a transformative strategy to mimic natural systems (figure 2). This strategy can restore landscape diversity and enhance soil and agroecosystem resilience (Russelle et al. 2007), and is especially important under increasing climatic fluctuations. Both perennial forages and food crops can complement each other in the same agricultural fields to buffer climate impacts, recycle C and nutrients, enhance soil attributes, improve biodiversity, and enhance other ecosystem services. Perennials can provide livestock feed, biofuel feedstock, and other products. They can also contribute to food security by enhancing the productivity of the adjacent food crops by providing shelter from wind and reducing water loss through transpiration. Perennial plant species provide more provisioning (i.e., biomass), regulating (i.e., soil and water quality), and supporting (i.e., biodiversity) ecosystem services compared to most row crops grown as monocrops and in systems with limited potential to provide multiple ecoservices (figure 3).

Incorporation of perennials into croplands requires the redesign of current agricultural systems. One of the options is growing perennials in marginally productive portions of the field and growing food crops (row crops) in productive areas of the field. Marginal portions of the cropped field can include eroded or erosion-prone, compacted or compaction-prone, flood-prone, sloping, low organic matter content, acid, or saline soils (Blanco-Canqui 2016). Because perennial plant species have deep and extensive root systems, they are more tolerant to low soil fertility and adverse soil conditions than row crops and can grow in relatively marginal lands, which can enhance the productivity of intercropped neighboring species. Perennial species provide significant amounts of aboveground and belowground (abundant and deep roots) biomass, which are essential to recycle water, C, and nutrients, while enhancing soil and agroecosystem resilience. Many variations on spatial and temporal multiple species design have been discussed in temperate and tropical regions (Francis 1986; Lin 2011).

Addition of deep-rooted perennial plant species to farming systems can restore some of the key ecosystem services and address growing concerns about degraded soil and environmental quality as well as reduced wildlife habitat and diversity. For example, in the United States, specifically in the US Midwest, much of the tallgrass prairie (about 95%) has disappeared due to the expansion of croplands (Gardner 2011). In this region, incorporating mono-

Figure 3

Perennials grown among or adjacent to annual crops can provide numerous ecosystem services.

Buffering climate

- Perennials provide protective cover to soil and moderate maximum and minimum soil temperature.
- Perennials absorb intense rainstorms, slow runoff, improve drainage, and thus reduce risks of flooding.
- Aboveground biomass of perennials covers the surface while the belowground biomass (deep extensive root network) stabilizes soil and enhances soil and agroecosystem resilience.

Sequestering carbon (C) in the soil

- Perennials can increase soil C pool from 0.1 to 3 Mg ha^{-1} y^{-1} (Blanco-Canqui 2010).
- Perennials can enhance soil C storage in deeper soil depths as grasses have greater root biomass than annual row crops.
- Marginally productive croplands with low initial soil C can rapidly accumulate soil C under perennial species.

Improving water quality

- Perennial vegetation and residues protect soil from water erosion.
- Perennials can improve water quality by reducing risks of nonpoint source pollution in runoff from agricultural fields. (Blanco-Canqui 2010; VanLoocke et al. 2016).
- Perennials increase soil organic matter content, which can filter and degrade pollutants in runoff.

Improving wildlife habitat

- Tall perennial species such as warm-season grasses can increase abundance of beneficial insects, birds, and other wildlife species (Blanco-Canqui 2010; Werling et al. 2014).
- Perennials provide cover, nesting, and shelter for wildlife species.
- Perennial bunch grasses provide quality habitat for wildlife even when moderately grazed or harvested at high cutting heights (10 cm).

Enhancing soil attributes

- Perennials can improve soil biodiversity and microbial processes through their extensive and abundant root biomass, which enhances soil buffering capacity.
- Growing perennials or their residues improve soil physical, chemical, and biological properties, which directly enhance soil resilience.
- Perennials improve soil aggregation, soil macroporosity, water infiltration, water retention capacity, and soil fertility.

cultures or mixtures of native perennial plant species such as warm-season grasses including switchgrass (*Panicum virgatum* L.), Indiangrass (*Sorghastrum nutans* [L.] Nash), big bluestem (*Andropogon gerardii* Vitman), miscanthus (*Miscanthus* × *giganteus*), and others into cropped fields can enhance multifunctionality of agroecosystems and address some of the concerns of degradation of ecosystem services. For example, narrow perennial strips across the slope can significantly reduce soil erosion and loss of nutrients and chemicals from fields. A modeling study from the Mississippi–Atchafalaya River Basin indicated that replacing 5% to 25% of current row crops with perennial miscanthus and switchgrass for cellulosic bioenergy production can reduce leaching of dissolved inorganic nitrogen (N) and runoff, reducing nonpoint source pollution from croplands (VanLoocke et al. 2016). Growing perennials in marginally productive lands not only can address demands for feed, biofuel, and fiber production but also restore the land with degraded ecosystem services, enhancing the overall agroecosystem resilience. Figure 3 highlights some of the ecosystem services that perennials deliver when grown in marginally productive and sloping croplands.

Intensifying Cover Crop Use. Cover crops have the potential to provide numerous ecosystem services to current agricultural systems (figure 4). Cover crops can buffer abrupt fluctuations in climate by providing surface protective cover and contributing to soil resilience. Cover crops can capture atmospheric C through sequestration in the soil, thus reducing buildup of C in the atmosphere. Cover crops can provide additional biomass for erosion control and water quality improvement under increasingly intense rainstorms. Belowground biomass (roots) can improve soil biodiversity, enhancing resilience of the soil (Blanco-Canqui et al. 2015). Intensifying current agricultural systems with the addition of cover crops is thus one of the potential strategies to enhance soil and agroecosystem resilience and delivery of ecosystem services.

Cover crops can also provide biofuel feedstocks and livestock feed. Recent studies have indicated that cover crops, particularly grasses, can produce significant amounts of cellulosic biomass for biofuel production (Baker and Griffis 2009). Similarly, livestock grazing or harvesting cover crops may not negatively affect other ecosystem services from cover crops such as erosion control, C sequestration, and improvement in soil properties. By producing biofuel and providing feed to animals, cover crops can address food security and environmental concerns (Franzluebbers and Stuedemann 2015; Blanco-Canqui et al. 2015).

Cover crops can be grown (1) along with main crops, (2) between harvest in one season and planting of main crops in the next season, and (3) during current fallow periods (i.e., crop–fallow) when soil often remains bare. This is especially important following a soybean (*Glycine max* [L.] Merr.) or other crop that leaves minimal residue after harvest. Cover crops are more effective companion practices when used with no-till systems than when used with conventional tillage systems. The reduced soil disturbance under no-till increases the effectiveness of cover crops for accumulating organic C in the soil and improving soil properties. However, it is also important to consider factors that affect cover crop performance and delivery of ecosystem services. The extent to which cover crops improve soil and agroecosystem resilience is site-specific and will depend on management (i.e., tillage, planting and termination times, seeding rates), amount of biomass produced, cover crop species, initial soil C level, soil type, climate (especially rainfall and temperature), and others (Blanco-Canqui et al. 2015; Poeplau and Don 2015).

Redesigning No-Till Cropping Systems. No-till adoption has consistently increased since the 1960s, particularly in South and North America. For example, in the United States approximately 35% of the cropland is under no-till management (USDA ERS 2010). Much of the rest of US cropland is under plow till and reduced till. It is well recognized that no-till is a leading conservation practice to conserve soil and water and reduce production costs, among other favorable consequences (Palm et al. 2014). However, challenges exist with this technology, some of which are listed in figure 5 (Palm et al. 2014). These challenges indicate that simply adopting no-till in hopes of enhancing and delivering all ecosystem services may not work in all scenarios, particularly under extreme climatic conditions.

The declining ecosystem services and increasing climatic extremes compel us to rethink and redesign current no-till systems to enhance their potential to build resilient soils and agroecosystems. One of the strategies consists of expanding the combination of no-till systems with improved companion practices such as including cover crops, semiperennial grasses or forages, diversified cropping systems, and other within-field diversity practices. Recent studies found that cover crop addition to no-till can enhance the potential of no-till to sequester soil C, capture precipitation, reduce water erosion, improve water quality, and improve soil biodiversity relative to no-till alone (Blanco-Canqui et al. 2015). Similarly, adding native perennial grasses (i.e., warm-season grasses) to no-till fields or rotating semiperennials (i.e., alfalfa [*Medicago sativa* L.]) with no-till row crops can enhance cropland quality under no-till to provide enhanced soil and agroecosystem resilience and provide multiple benefits compared with no-till monocrops or with simplified rotations. Because no-till management often causes stratification of C and more nutrients to accumulate near the surface due to surface residue mulching and reduced soil mixing, incorporating deep-rooted perennials in no-till rotations can contribute to subsoil nutrient recycling and C sequestration in lower depths of the soil profile.

Use of monocrops or simplified rotations with increased use of inorganic fertilizers and pesticides has raised concerns about agricultural sustainability and resilience (Lin 2011). Even when managed under no-till systems, monocrops can be less resilient and sustainable than diversified cropping systems. Thus, expanding the use of diversified no-till cropping systems with cover crops and perennials/semiperennials is a valuable strategy not only to improve soil ecosystem services but also to manage weeds and pests. The latter are major concerns in no-till production systems with simplified rotations (Lin 2011; Powlson et al. 2014). Diversified cropping systems have some of the attributes of natural systems, return different quantities and qualities of aboveground and belowground residues, and are thus more resilient than monocropping systems. For example, adding mixed cover crop species to no-till continuous corn (*Zea mays* L.) can be a transformative approach to intensify and diversify such systems to enhance ecosystem services. No-till management with little or no residue left after grain harvest may be no better than conventional tillage to protect soils. Cover crops can supplant crop residues and enhance the potential of no-till to provide soil services. Also, soil changes and other benefits from no-till are often measurable in the long term (more than five years), but the addition of improved practices can accelerate no-till benefits for delivering enhanced services and enhancing the overall resilience of agroecosystems.

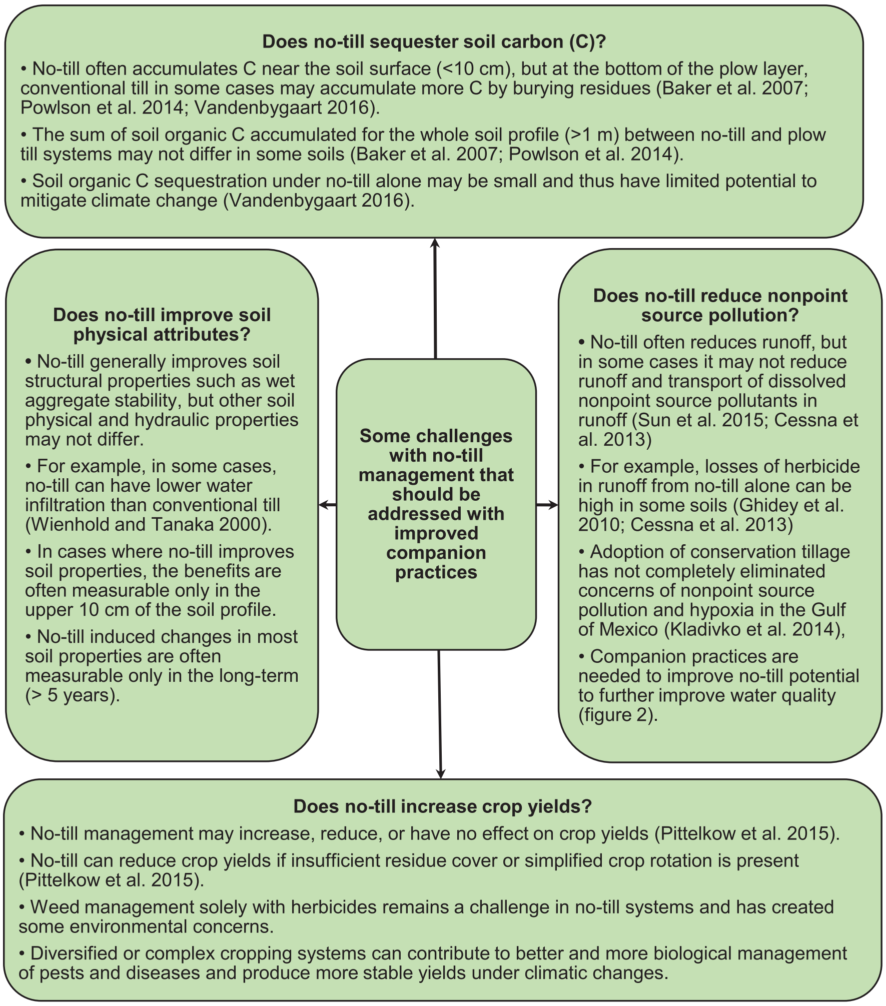
Figure 4

Cover crops can enhance soil and agroecosystem resilience and buffer abrupt climatic fluctuations.

Buffering rainstorms, flooding, and droughts	•Cover crops protect the soil and reduce runoff and losses of sediment, sediment-associated C, and nutrients. •Cover crops improve water infiltration and drainage under intense rainstorms, reducing risks of flooding. •Cover crop residues can conserve water in dry years and increase water retention capacity by increasing soil organic matter content.
Buffering temperature fluctuations	•Cover crops insulate the soil and reduce abrupt fluctuations in soil temperature, contributing to soil resilience against fluctuating climate. •Soils with abundant residue are cooler in summer and warmer in winter than soils with no residue cover (Blanco-Canqui et al. 2015). •Cover crops reduce the number of freeze-thaw and dry-wet cycles by providing surface cover.
Sequestering carbon (C) in the soil	•Cover crops generally increase soil C from 0.1 to 1 Mg ha^{-1} y^{-1} particularly in the long term (>5 years: Blanco-Canqui et al. 2015; Poeplau and Don 2015). •Deep-rooted cover crops can accumulate soil C in deeper soil depths. •Increased soil C concentration improves soil structural and hydraulic properties, enhancing soil resilience.
Improving water quality	•Cover crops reduce losses of nutrients and pesticides, lowering risks of nonpoint source pollution from agricultural fields. •For example, cover crops can reduce nitrate (NO_3) loadings into the Mississippi River Basin by about 20% (Kladivko et al. 2014). •Cover crops increase the ability of no-till cropping systems to reduce runoff and losses of dissolved nutrients (Kaspar et al. 2001).
Enhancing nutrient cycling and sustaining yields	•Cover crops reduce nitrogen (N) losses and sustain yields by (1) reducing leaching of NO_3, (2) scavenging extra N, (3) reducing runoff nutrients, and fixing N (Kaspar et al. 2001; Tribouillois et al. 2016). •Cover crops can stabilize inorganic N applied to main crops in the root zone and thus increase its effectiveness (Lacey et al. 2015). •Cover crops can increase crop yields in dry years in regions with high precipitation (Daigh et al. 2014). •Cover crops also influence crop production by reducing soil compaction and increasing the water content so that some soils can be trafficked without compacting soil (Blanco-Canqui et al. 2015).

Figure 5

Some challenges with no-till management when managed alone without simultaneous improved practices such as addition of cover crops, semiperennials, and others.



Potentials of Temporally and Spatially Diverse Cropping Systems. As described in the previous sections, the move toward simplified sole crop (monocrop) strategies for farming has been fostered by an industrial revolution that freed many farmers, especially in North America, from the more laborious and time-consuming tasks of raising and harvesting crops. Yet many concurrent transformations have supported this transition, such as substitution of chemical fertilizers and pesticides for internal resources and diversified designs for raising crops, patents on seed that make it difficult for farmers to save their own on the farm, commodification and industrialization of food and removal of its local identity, and massive financial inputs into research to improve the labor- and land-efficiency of this system (IAASTD 2009). With this industrial agenda driving research and neoclassical economic metrics providing short-term evaluation of profits and loss, it is not surprising that nonmonetized outcomes such as ecosystem services have been left on the sidelines. Redesigning cropping systems through temporal and spatial diversification is a potential strategy to enhance ecosystem services (Lin 2011).

Once considered outdated, traditional methods that were destined to disappear with the immediate successes of the Green Revolution, multiple cropping systems are increasingly becoming recognized as providing efficient and productive strategies to use scarce production resources and buffer systems against fluctuations in climate (Francis 1986; Lin 2011). Location-specific applications of spatially diverse cropping systems such as intercropping should be considered to enhance ecosystem services (Vandermeer and Perfecto 2016). Diversified cropping systems with greater plant species richness than monocrops can promote recycling of nutrients from lower depths and lead to higher soil C stocks. Diverse crops with diverse rooting depths and configurations may also impact soil physical properties by increasing soil aggregation, porosity, and water infiltration (Lin 2011). Legume and cereal combinations may be complementary because of different root systems that explore unique niches in the soil profile. For example, intercropping with trees in agroforestry systems has high potential to recycle nutrients from deep in the profile, improve soil biology and chemistry, and positively affect soil C and physical properties, enhancing overall soil health and resilience (Kremer and Kussman 2011).

Integrating Livestock with Diversified Cropping Systems. The above transformative strategies can blend with livestock production to further enhance agroecosystem resilience and maximize ecosystem services from the same piece of land. While integrated crop-livestock systems are not uncommon worldwide, specialized agriculture has resulted, particularly in industrialized countries, in the separation of crops and animals; this change has simplified agricultural landscapes and led to reduced ecosystem services (Sanderson et al. 2013; Brummel and Nelson 2014). For example, confinement of animals in feedlots has reduced multifunctionality of agroecosystems and increased both environmental concerns and production costs. Crops and livestock systems can interact and mutually benefit from integration (Sanderson et al. 2013). Cropping systems with complex rotations, cover crops, and perennial forages can provide feed and contribute to livestock profitability, while grazing animals can contribute to the sustainability of cropping systems by recycling C and nutrients (i.e., manure) and improving soil biological functions.

Grazing crop residues or cover crops when soil is frozen or not wet can be a potential strategy to increase multifunctionality of cropping systems. Grazing and harvesting cover crops and perennials may not significantly reduce the soil ecosystem services from cover crops (Franzluebbers and Stuedemann 2015). Indeed, this interdependence of benefits can enhance multifunctionality of agricultural systems (Brummel and Nelson 2014). Integrated crop-livestock systems can increase soil C sequestration, enhance nutrient cycling, improve soil biology, and increase crop production. Integrating crop production with livestock production is gaining interest, but further research and financial incentives are needed for increasing diversity and complexity of landscapes with complex cropping and livestock systems to enhance resilience and ecosystem services of agricultural systems.

The various strategies discussed here complement each other to improve soil and agroecosystem resilience and enhance ecosystem services (figures 1 and 2). Because a single universal transformative practice does not exist to address the declining ecosystem services in agricultural lands worldwide, region-specific redesign of agricultural landscapes and refinement of strategies imitating natural systems is needed to build resilient soils and agroecosystems for an uncertain climate. In fact, there is need for field-specific, farm-specific, and agroecosystem-specific solutions rather than a strategy that promotes menu-based farming and homogeneity of landscapes. Further expansion or implementation of such strategies will require the development of management guidelines and policy structures.

CONCLUSIONS

Most current agricultural systems are not designed to deliver multiple ecosystem services. There is also a dearth of research for system resilience against increasing climatic fluctuations. Most current farming systems are primarily designed to increase crop or livestock production to generate short-term economic benefits, and not specifically to build resilient soils that support sustainable agroecosystems. Redesigning current agricultural landscapes with transformative strategies that mimic natural systems should be a priority to enhance soil and agroecosystem resilience and contribute to restoring ecosystem services.

Ecologically informed farming systems can contribute much more to ecosystem services than the current industrial monocultures that dominate agriculture in the industrialized world. Potential strategies include integrating perennial plant species with food crops, intensifying use of cover crops, redesigning current no-till cropping systems, and increasing integration of crop-livestock systems (figures 1 and 2). These strategies can buffer impacts of extreme climatic fluctuations, sequester soil C, improve water quality, increase soil biodiversity, and enhance wildlife habitat and diversity while delivering essential services such as food, fuel, fiber, and feed production. Biodiverse farming systems can also lead to more diverse income streams and cash flow throughout the year. Policy actions can foster strategies to enhance soil and agroecosystem resilience and ecosystem services on both local and global scales, but viable farming systems must be developed and demonstrated before they will be able to impact the policy agenda.

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