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# Adaptive management for soil ecosystem services

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ABSTRACT

Ecosystem services provided by soil include regulation of the atmosphere and climate, primary (including agricultural) production, waste processing, decomposition, nutrient conservation, water purification, erosion control, medical resources, pest control, and disease mitigation. The simultaneous production of these multiple services arises from complex interactions among diverse aboveground and belowground communities across multiple scales. When a system is mismanaged, non-linear and persistent losses in ecosystem services can arise. Adaptive management is an approach to management designed to reduce uncertainty as management proceeds. By developing alternative hypotheses, testing these hypotheses and adjusting management in response to outcomes, managers can probe dynamic mechanistic relationships among aboveground and belowground soil system components. In doing so, soil ecosystem services can be preserved and critical ecological thresholds avoided. Here, we present an adaptive management framework designed to reduce uncertainty surrounding the soil system, even when soil ecosystem services production is not the explicit management objective, so that managers can reach their management goals without undermining soil multifunctionality or contributing to an irreversible loss of soil ecosystem services.



## 1. Introduction

Ecosystem services provided by soil include regulation of the atmosphere and climate, primary (including agricultural) production, waste processing, decomposition, nutrient conservation, water purification, erosion control, medical resources, pest control, and disease mitigation (Wall et al., 2004; Bardgett, 2005; de Deyn and Van Der Putten, 2005; Wall et al., 2015). Many of these services emerge from cryptic processes in the rhizosphere, creating uncertainty for managers seeking to improve or increase the delivery of soil ecosystem services (Baer et al., 2012). Adaptive management is intended to reduce uncertainty surrounding key questions in the landscape of interest by adjusting procedures as new information is gained (Allen and Garmestani, 2015), providing the opportunity to manage soils for multiple services while learning what strategies work in individual environments. Here, we discuss the unique challenges the soil system presents to management and then offer an adaptive management approach for soil ecosystem service production that can be applied to multiple management contexts.

### 1.1. Multifunctionality: the role of biodiversity in ecosystem service production

Ecological multifunctionality refers to the simultaneous production of numerous ecosystem services, and relies on a diverse community of species with a variety of functional traits (Wall et al., 2004; Gamfeldt et al., 2008; Maestre et al., 2012; Wagg et al., 2014). For example, the functions of nutrient transformation, primary production, and carbon sequestration arise from the processes and interactions of and among a variety of species in one place in time (de Vries et al., 2012; Bradford et al., 2014). To maintain multifunctionality through time, a diverse community includes

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functional replacements for species excluded by shifting conditions ("functional redundancy"), or species with high plasticity (Isbell et al., 2011; de Vries et al., 2012). The link between multi-functionality and biodiversity is especially apparent in communities with low diversity or in the case of a specialized function, (Nielsen et al., 2011).

In terrestrial ecosystems, aboveground-belowground functioning is tightly linked through the rhizosphere (Bardgett and Wardle, 2003; de Deyn and Van Der Putten, 2005) (Fig. 1). Plants exude up to 40% of their fixed carbon into the rhizosphere as easily decomposable carbon (e.g., glucose), which is the major "currency" of the belowground system (Lynch and Whipps, 1990; Brussard, 2012). Relative to the rest of the ecosystem, bacterial biomass is not impressive. Yet bacterial transformations of materials and energy in the rhizosphere influence whole ecosystem functioning (Alphei et al., 1996). These microbiota mineralize nutrients for plant uptake (de Deyn and Van Der Putten, 2005), permanently remove reactive nitrogen from the system (Schlesinger and Bernhardt, 2013), remediate toxins (Reynolds and Skipper, 2005), alter gas and water flow around roots by influencing soil aggregation (Jastrow, 1987; Kennedy, 2005; Kibblewhite et al., 2008), and serve as a food source for microfaunal grazers like protozoa and nematodes (Griffiths, 1990; de Deyn and Van Der Putten, 2005). These microfauna in turn provide food for higher tropic levels, excrete nutrients for plant uptake, and engineer the soil (Bonkowski, 2004; Ekelund et al., 2009). Lack of readily available nutrients for plant uptake may induce root carbon exudation to stimulate the release of nutrients tied up in bacterial biomass, creating potential aboveground-belowground feedbacks in the rhizosphere, and influencing where and how a plant allocates its carbon stores (growth, maintenance, defense, exudation, reproduction, etc.) (Bonkowski, 2004; de Deyn and Van Der Putten, 2005). In addition to root exudates, plants provide carbon to the soil surface and belowground through aboveground litter fall and root turnover, influencing the soil food web through changes in the quality and quantity of inputs (Eisenhauer et al., 2013; Lange et al., 2015; Steinauer et al., 2015). Plants also interact directly with various herbivores, pollinators, pathogens, and symbiotic endophytes aboveground; and root herbivores, parasites, pathogens, symbiotic nitrogen fixing bacteria, and arbuscular mycorrhizal fungi

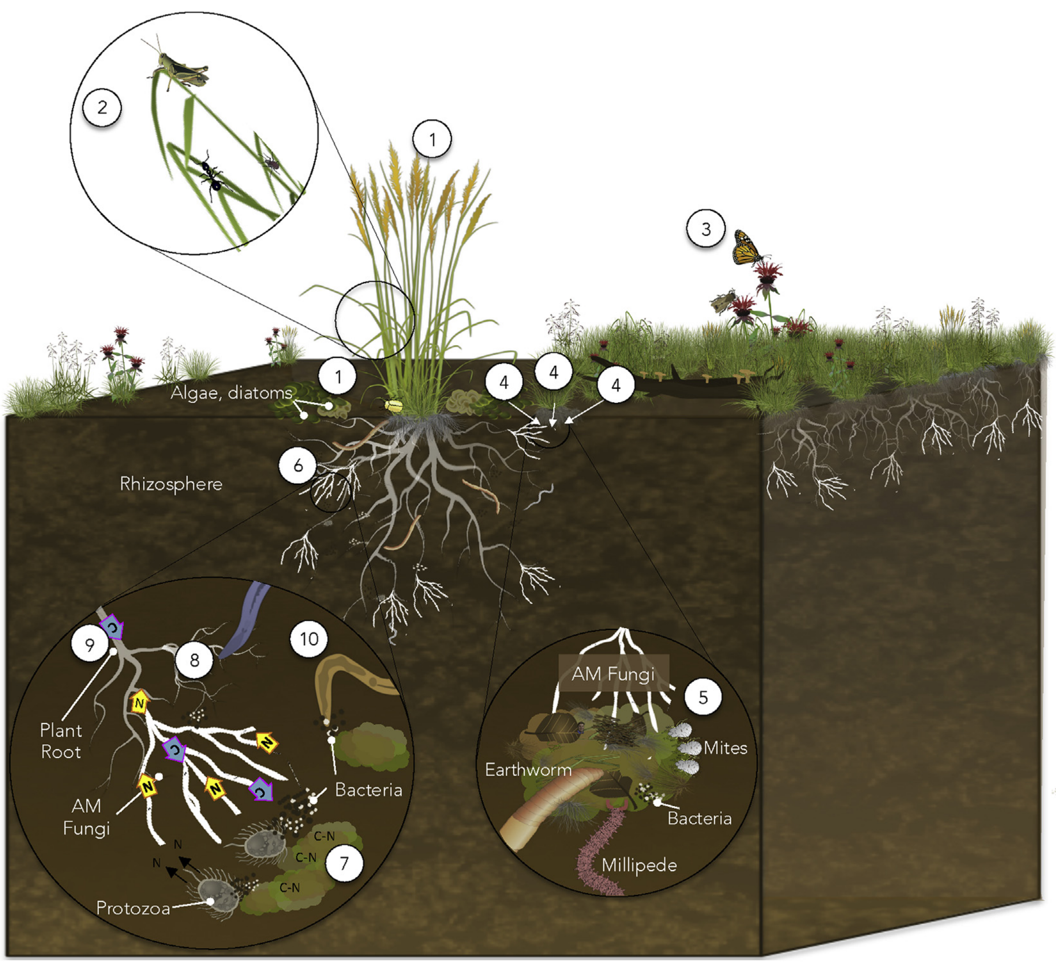


**Fig. 1.** A conceptualization of the tightly coupled aboveground-belowground biodiversity and functioning. Primary production (1) is the ultimate source of energy in all ecosystems. Plant materials provide food for a variety of aboveground chewing, sucking, mining (2), and pollinating (3) insects. These plant-insect interactions affect plant chemistry, plant community structure, plant and insect dispersal, and an abundance and diversity of other herbivores and higher trophic levels in the ecosystem (not all shown) (de Deyn and Van Der Putten, 2005). Changes in the quantity and/or quality of litter inputs to the soil (4) can result from aboveground herbivory, and alter the food source for a variety of belowground detritivores (5) (Wardle et al., 2002; de Deyn and van der Putten, 2011). Bacteria, protozoa, and arbuscular mycorrhizal (AM) fungi in the rhizosphere (6) directly influence the mineralization of organic carbon and nitrogen (C–N) stored in humus (7), affecting available nutrients for plants, who may alter fine root turnover (8), and/or release labile carbon (9) to the surrounding soil microbiota in response, stimulating mineralization activity, and indirectly influencing higher trophic levels, such as nematodes that feed on roots and bacteria (10) (Brussaard, 2012). Soil nutrient availability in turn influence plant community structure (Isbell et al., 2013), affecting the quality and quantity of litter inputs back to the soil and thus tightening aboveground-belowground diversity and functional linkages. Vector symbols used in the figure courtesy of Tracey Saxby, Jane Hawkey, and Dieter Tracey of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

belowground (Bezemer and van Dam, 2005; de Deyn and Van Der Putten, 2005; Bardgett and van der Putten, 2014). These interactions affect plant community structure and plant contributions to ecological multifunctionality, such as biomass production, invasion resistance, and belowground carbon sequestration (Zavaleta et al., 2010; Isbell et al., 2011; Eisenhauer et al., 2013). This tight coupling of aboveground-belowground functioning and diversity can, if ignored by management, contribute to non-linear losses of soil ecosystem services.

### 1.2. Soil feedbacks and non-linear systems shifts: implications for management

Given the generally positive relationships between biodiversity and multifunctionality, greater ecosystem service outputs could in theory be achieved by managing for higher plant and soil biodiversity. However, there are spatial and temporal constraints on the ecosystem services that can be produced from a given landscape (Birge et al., *this issue*). For example, intensive agriculture generates valuable textile and food ecosystem services (MA, 2005), but reduces soil diversity and multifunctionality (Brussaard, 1997; DeFries et al., 2004). The cost of these tradeoffs between agricultural production and biodiversity may not be apparent until a threshold is exceeded and ecosystem services are lost, or significantly reduced (Walker and Salt, 2008). In many cases, this unintended loss of ecosystem services occurs suddenly and is persistent (Holling and Meffe, 1996; Scheffer et al., 2001).

Indeed, slowly developing feedbacks between intensive production of a single agroecosystem service and soil functioning have been responsible for multiple types of shifts associated with a catastrophic loss of ecosystem services (Pitman, 2002; Peters et al., 2015). Soil salinization in arid agricultural areas is often a result of altered plant–soil feedbacks under intensifying irrigation (Smedema, 1990; Folke et al., 2004). In Australia, replacement of native woody vegetation with shallow-rooted wheat crops results in rising groundwater tables. This leads to the mobilization of deep salt stores to shallower soil depths (McFarlane et al., 1992), negatively impacting plant productivity and soil biological activity (Pankhurst et al., 2001; Gordon et al., 2003). Due to continual groundwater recharge and low mean annual precipitation (i.e., lack of flushing events), soil salinization of croplands is a persistent problem in much of Australia (Gordon et al., 2003). Globally, irrigation is also major driver of soil salinization. In arid regions, rapid evaporation of impure irrigation water leaves behind salt residues on the soil surface, and waterlogging of soil with natural salt deposits may mobilize salt upwards (Sumner, 1995). Loss of ecosystem services associated with salinization due to agricultural intensification is not a new problem – it was a significant contributor to the dissolution of the Sumerian nation-state in ~1800 BCE (Jacobsen and Adams, 1958), and losses of riverine and wetland ecosystem services from saline runoff underscores the potential of salinization for long-term, watershed-scale impacts (Hart et al., 1991; Delaney et al., 2015). Indeed, the agricultural and ecological effects of soil salinization are widespread (e.g., Rietz and Haynes, 2003; Houk et al., 2006) with approxiamately 50% of global agricultural soils experiencing some degree of salinization, resulting in agricultural costs of roughly US $12 billion annually (Smedema and Shiati, 2002; Pitman and Läuchli, 2002).

Another possible non-linear system response to intensive agricultural ecosystem services production is desertification (Peters et al., 2013; Verstraete et al., 2009). Desertification is a broad-scale and persistent reduction in productivity that often arises from interactions among climatic, ecological, and social factors, and occurs in arid, semi-arid, tropical, temperate, and high-latitude ecosystems (Verstraete, 1986; Verstraete et al., 2009). It is often characterized by a relatively sudden shift from a system characterized by productive, native, perennial plant cover to one dominated by high bare ground, annual, non-native, and/or xeric shrubby plant cover (Peters et al., 2015). Replacement of deep-rooted, drought tolerant perennial grassland species by drought intolerant wheat crops in the early 20th century U.S. Great Plains resulted in a reduced rhizosphere and high bare ground cover contributing to a loss of soil stability. An especially intense and long lasting drought in the 1930s (Miao et al., 2007; Cook et al., 2009) was the proximate cause of a desertification event that displaced nearly 39 million hectares of topsoil across the Southern Great Plains, USA. In the case of the Dust Bowl, as is common in desertification, a stochastic event triggered catastrophe by overwhelming other, previously altered system feedbacks, making it difficult to disentangle the individual drivers of system state changes (Rietkerk and van de Koppel, 1997; Peters and Havstad, 2006; Scheffer et al., 2001). Yet, poor land management at least partially directly contributes to the 12 million hectares of newly desertified land globally each year (UNCCD, 2011), resulting in losses to agricultural, cultural, hunting, tourism, and carbon sequestration ecosystem services (UNCCD, 2013), at a cost of roughly US $3 trillion (~3–5% of global GDP) annually (Berry et al., 2003).

Even when agriculture is ceased before an apparent threshold is crossed, high concentrations of soil phosphorus and nitrogen can persist in soils, undermining restoration targets due to their unexpected interactions with the mechanisms underpinning those targets (Isbell et al., 2013; Graham and Mendelssohn, 2016). For example, "Hole-in-the-Donut," a tract of agricultural land formerly surrounded by Everglades National Park, Florida, USA, was incorporated into the park in 1975 after eighty years of intensive agricultural pesticide and fertilizer inputs. Agricultural management of the site included bedrock plowing, which crushes and mixes limestone bedrock into the overlying marl and organic horizons, fertilizer inputs, and pesticide application. As a result, when the park purchased Hole-in-the-Donut, and herbicide application was halted, its deep, nutrient-rich soil provided the conditions necessary for a nearly immediate invasion by the non-native shrub *Schinus terebinthifolius* (also know as Brazilian pepper or Christmas berry) (Smith et al., 2011; Ewel, 2013). Exacerbating the invasion is *S. terebinthifolius*' beneficial association with mycorrhizal fungi, which are obligate aerobes and thus uncommon among native plants inhabiting the hydric soils characteristic of the Everglades ecosystem (Ewel et al., 1982). Despite intensive mechanical tree removal, herbicide application, and prescribed burning on the site, *S. terebinthifolius* persisted for decades, ultimately forming a near monoculture on the site (Ewel et al., 1982; Smith et al., 2011). Eventually, managers removed the entirety of the phosphorus-rich, rock-plowed soil down to the bedrock over the entire 22 $km^2$ expanse of Hole-in-the-Donut –a resource intensive undertaking. Eleven years after soil removal, Hole-in-the-Donut had nearly 4 cm of newly formed topsoil, and was dominated once again by native vegetation (O'Hare, 2008; Smith et al., 2011).

As these examples illustrate, when landscapes are optimized for the intensive production of a single or few services, an unexpected feedback may overwhelm other processes, pushing the system across a threshold where not even the desired service can be adequately produced. Soil degradation, such as salinization, erosion, and changes in nutrient cycling, is recognized as a threat to the security of global food and fiber production, water purification, biodiversity, and climate regulation (CEC, 2006; Lal, 2010; McBratney et al., 2014). While management action may seem risky in systems with past susceptibility to catastrophic shifts, the cost of inaction could be higher still. Thus, as managers seek to improve the output of soil multifunctionality, or at least ensure that their management actions do not contribute to non-linear system shifts arising from feedbacks with the soil system, it is imperative to reduce uncertainty surrounding management decisions. One such approach is adaptive management, which offers managers a way to proceed with management while learning about their system so that soil ecosystem service output can be increased, and critical thresholds avoided.

## 2. Incorporating soil into an adaptive management framework

In any ecosystem, there is a limited availability of ecosystem services. Top-down constraints such as climate, topography, and soil mineralogy dictate the range of services an ecosystem can provide, and management decisions further constrain the realized set of ecosystem services.

No single ecosystem can produce every service possible at its optimized output consistently throughout space and time due to natural ecological variability, but a diverse, functionally connected aboveground-belowground system contributes to ongoing multifunctionality and safeguards against undesirable regime shifts (Wall et al., 2004; Foley et al., 2005). In a management context, stakeholders may not be immediately concerned with ecosystem service losses associated with potential future regime shifts. Yet the costs associated with these shifts are high, and complex soil feedbacks may be poorly understood, creating uncertainty around key processes. Managers attempting to generate multiple ecosystem services also face tradeoffs – especially if their plans require a reduction in biodiversity.

Adaptive management is designed to reduce uncertainty and winnow amongst competing hypotheses of system response as management proceeds (Allen and Garmestani, 2015). Adaptive management involves generating alternative hypotheses, testing these hypotheses and adjusting management in response to outcomes, and embracing unpredicted events as opportunities to reveal mechanisms and unknown relationships (Williams, 2001). Here, we present an adaptive management framework designed to reduce uncertainty surrounding the soil system and soil ecosystem service tradeoffs –even when soil ecosystem services production is not the explicit management objective.

### 2.1. The soil adaptive management cycle

Adaptive management is appropriate when there is uncertainty regarding response to management, but an ability to manage (i.e., there is "controllability") (Allen et al., 2011). An adaptive management cycle begins with explicit conceptual models of the system at hand, and addresses a management problem with actions that can be tested as alternative hypotheses through monitoring and assessment (Fig. 2). Knowledge gained through evaluation of monitoring data can be used to improve the next round of adaptive management. Regardless of whether the management goal is enhancing soil ecosystem services production, a straightforward and inexpensive way to improve an adaptive management plan is to ensure that information about the belowground is integrated into the conceptual model of the system when the problem is defined and objectives identified. This inclusion may reframe the decision making steps of the adaptive management approach by outlining important belowground feedbacks that might otherwise go unmonitored. After incorporating belowground information into their conceptual model, a manager may then modify management actions and monitoring variables to account for belowground processes and feedbacks. The significance of the soil variables monitored (Table 1) to the management problem can then guide the manager's future allocation of monitoring resources. This contrasts with trial and error management, in which management is only adjusted when an error occurs, and lack of error is interpreted as a successful application of management, regardless of the mechanism driving system behavior. Adaptive management promotes learning about the system regardless of outcome (Holling, 1978), and is thus well suited for the soil system, with its complex aboveground-belowground linkages and potential for nonlinear response to management. By promoting the inclusion of soil monitoring variables in the adaptive management cycle, managers may improve the output of soil ecosystem services such as food and fiber production, biodiversity, water purification, carbon sequestration, atmospheric and hydrologic regulation, erosion control, and pest and pathogen control (Wall et al., 2004, 2012).

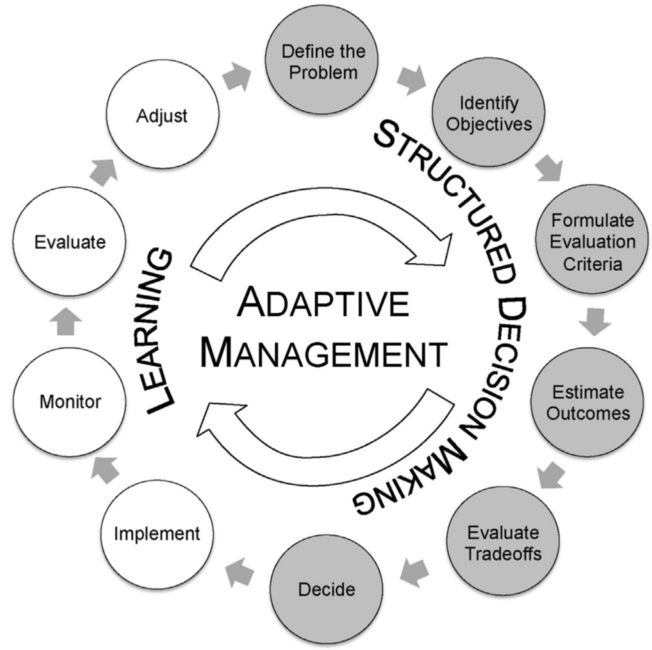


**Fig. 2.** The adaptive management cycle [modified from Allen et al. (2011)].

An adaptive management approach that accounts for soil components can reduce overall system uncertainty. However, the soil system operates at multiple scales across space and time –not all of which are commensurate with a typical management program. Moderately slow variables that vary over months to decades could be missed by a cursory inclusion of soil components in an adaptive management plan (Table 1). Similarly, measurements of a single or a few time points of a fast-changing variable, such as microfaunal diversity, may not capture a significant trend.

In the examples of desertification, salinization, and a species invasion, feedbacks between the aboveground and belowground may contribute to a non-linear and persistent reductions in ecosystem services. The processes driving these shifts may be detected and avoided using adaptive management. By adding a soil adaptive management cycle to an overall adaptive management program (Fig. 3), managers can continue to address their fundamental management objective while accounting for a belowground means (supporting) objective that could otherwise be overlooked and thus potentially result in a persistent loss of ecosystem services.

Much like the main adaptive management cycle, the soil adaptive management cycle should be tailored to the system and problem at hand, and alternative hypotheses should address key uncertainties about soil system mechanisms. Many ecosystems have multiple possible alternative, persistent states, and soil feedbacks may not contribute meaningfully, either ultimately or

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**Table 1**
Testable soil variables, their speeds, and the associated ecosystem system services which they help to maintain. Approximate time scales for each variable include: Very Slow = millenia, Slow = centuries, Moderately Slow = decades, Moderately Fast = years, or Fast = seasons). The level of estimated training or soil-related expertise required (Low, Medium, or High) and cost estimates for field and laboratory measurements (Low, Medium, or High) are also provided.

| Variable | Variable speed | Associated ecosystem services | Expertise | Cost[a] |
|---|---|---|---|---|
| Texture | Very slow | Landscape diversity, primary productivity, $CO_2$ sequestration | Med. to high | Low to med. |
| Horizon depth | Slow | Erosion control, primary productivity | Med. to high | Med. to high |
| Compaction/bulk density | Moderately Fast | Generation of soil structure, runoff control, water-holding capacity, nutrient cycling | Medium | Low to medium |
| Aggregation | Moderately Fast | Erosion control, landscape diversity/microhabitats, $H_2O$ and nutrient transport, $CO_2$ sequestration | Med. to high | Low to high |
| Root biomass | Moderately Fast | Erosion control, maintenance of above/belowground biodiversity, soil structure, $CO_2$ sequestration, porosity | Med. to high | Low to high |
| Nematodes | Moderately fast | Bioturbation, decomposition, soil porosity, biodiversity, nutrient mineralization, $CO_2$ sequestration | Med. to high | Low to high |
| Surface residue | Moderately fast | Topsoil formation, microhabitats, $CO_2$ sequestration, soil stability, water-holding capacity | Low to med. | Very low |
| Fungal biomass | Fast to moderately fast | Biodiversity, primary productivity, $CO_2$ sequestration soil structure, nutrient mineralization | Med. to high | High |
| Salinity | Slow | Primary productivity, biodiversity, habitat quality | Med. to high | Med. to high |
| Trace nutrients (e.g. iron, manganese) | Slow | Landscape diversity, primary productivity, $CO_2$ sequestration | High | Med. to high |
| Cation exchange capacity (CEC) | Moderately slow | Soil fertility, primary productivity | Med. to high | Low to high |
| Total carbon | Slow to moderately fast | Soil stability, primary productivity, $CO_2$ sequestration, water-holding capacity, biodiversity | High | Med. to high |
| Nitrogen availability | Slow to fast | Soil fertility, biodiversity, primary productivity, $CO_2$ sequestration | Med. to high | Low to high |
| Total organic matter | Moderately fast | Soil stability, fertility, microhabitats, water cycling, nutrient mineralization | High | Med. to high |
| Soil pH | Fast | Nutrient cycling, microbial activity, decomposition | Low to med. | Low |
| Water-holding capacity | Slow | Irrigation, water cycling, nutrient cycling | Med. to high | Low to high |
| Infiltration | Moderately slow | Runoff control, water cycling, nutrient cycling | Low to med. | Low to med. |
| Decomposition | Fast | Nutrient cycling, topsoil production, soil stability, fertility, bioremediation | Med. to high | Low to high |
| Plant defense compounds | Fast | Primary productivity, pathogen control, nutrient cycling | High | High |

[a] Test prices are from test package pricing listed by Gunderson (2014), Ward Labs (wardlab.com) in Kearney, NE and the Cornell Soil Health lab in Ithaca, NY (soilhealth.cals.cornell.edu).

proximately, to every critical shift among states. The soil's potential significance in a given state shift should be hypothesized and *a priori* system indicators formulated during the structured decision making stage, and monitored during the learning stage of the main adaptive management cycle (Fig. 3). Depending on the system, these indicators may include increasing bareground cover, or a change in aboveground plant diversity (e.g., the loss of productive native species), both of which are closely associated with belowground functioning and biodiversity (Wardle et al., 2004; Bardgett et al., 2014). Because belowground-aboveground linkages create complex feedbacks, simple cause and effect relationships are difficult to ascertain from changes in the aboveground system alone, and instead require a soil adaptive management cycle to explore mechanistic relationships. For example, a one-time measure of bareground may not indicate a meaningful reduction in belowground functioning, but persistent or otherwise unexplainable bareground could suggest belowground feedbacks in need of further probing. Setting threshold levels of indicators that, once reached, initiate the soil adaptive management cycle can guide soil management (much like a predetermined threshold of invasive species abundance that, once exceeded, triggers specific management actions, e.g., van Wilgen and Biggs [2011]). When a soil adaptive management cycle is initiated, alternate hypotheses should be developed and tested to address whether the system uncertainty is arising from feedbacks with the soil system. As uncertainty is reduced or resolved in the soil adaptive management cycle, different outcomes can arise. A new set of hypotheses can be tested in another round of the soil adaptive management cycle to explore additional belowground uncertainty. Alternatively, information about the belowground system may reveal important uncertainties regarding the fundamental management objective, resulting in a new set of hypotheses to be tested in the main adaptive management cycle, i.e., double loop learning (Lee, 1993).

By identifying alternative hypotheses and indicators based on soil ecosystem services and thresholds to which the system may be vulnerable, managers have explicit targets that allow them to proactively decide when to devote additional resources to monitoring and learning about the soil system (a means objective) while meeting their fundamental objective. For example, a perennial grassland system may have an *a priori* determined management threshold for bareground (i.e., % extent, duration, or both). If a perennial grassland experiences a broad shift to a desertified state, aboveground-belowground activity may be isolated to spaces occupied by shrubby or xeric plants, and the interspaces barren, reinforcing the persistence of the alternative state (Peters et al., 2015). When evaluation of the bareground monitoring data triggers a soil adaptive management cycle, a conceptual model of the system can guide managers to measure system-specific and problem-specific soil variables, such as root biomass, fungal biomass, soil nutrient status, and cation exchange capacity (Table 1) in the bareground versus under vegetation over multiple sampling time points. Monitoring these variables as the management action proceeds can help explore hypotheses regarding the proximate and ultimate drivers of a system shift that would undermine not only

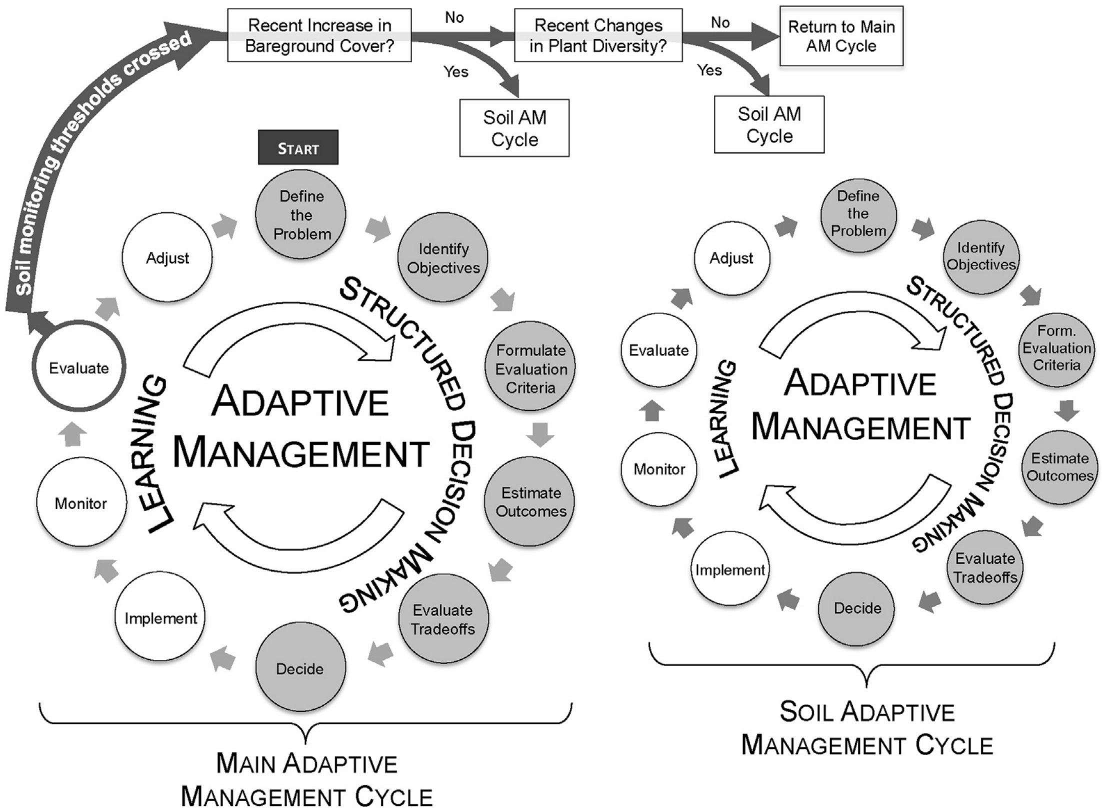


**Fig. 3.** An adaptive management framework for reducing uncertainty in the soil system while proceeding with the fundamental management objective.

soil ecosystem services but also the fundamental management objective.

Eventually, uncertainty surrounding the soil in a management plan should be also be resolved in a way that eliminates the need for a soil adaptive management cycle, either by identifying the soil monitoring variable(s) for inclusion in the main cycle, or because new information from the soil system alters the overarching, fundamental adaptive management objective. There may be no simple management recipe for increasing belowground multifunctionality and avoiding regime shifts, but this approach offers a structured way to proceed with management while constantly seeking to uncover mechanistic relationships. By learning while managing the aboveground and belowground as a complex, integrated system, a more nuanced and complete understanding of the system can emerge as management proceeds.

## 3. Conclusion

Drivers of global change such as global nitrogen deposition, climate change, and species invasions are creating uncertainty surrounding the future of soil biota and the ecosystem services they underpin. Poor land management that optimizes intensive production of a narrow suite of ecosystem services may contribute to non-linear, persistent losses of soil ecosystem services. Thus, in order to preserve the essential, immeasurably valuable (Pascual et al., 2015) benefits soil provides to human society, there is a pressing need to manage ecosystems with diverse, multifunctional belowground systems (Wall et al., 2015) while reducing uncertainty surrounding belowground response to management and global change. By reducing this uncertainty, adaptive management can target biodiversity objectives while avoiding critical system thresholds on a rapidly changing planet.

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