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Cover Crops and Soil Ecosystem Services

1.1 Cover Crops

According to the Soil Science Society of America, cover crops are defined as a "*close-growing crop that provides soil protection, seeding protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. When plowed under and incorporated into the soil, cover crops may be referred to as green manure crops*" (SSSA, 2022). Cover crops are not entirely new. Their use dates back over several millennia or probably to the origins of agriculture. Literature indicates that cover crops were used as green manure by civilizations in eastern Asia and ancient Rome approximately 3000 years ago (Groff, 2015; Lipman, 1912). Ancient civilizations used cover crops such as legumes as a source of essential nutrients to support soil fertility and productivity. In early times, cover crops were normally incorporated into soil to accelerate decomposition and improve soil fertility and thus were synonymous to green manure. In the U.S., Native Americans often used a mix of crops to improve crop diversity, which portrayed cover crop mixes (Groff, 2015). In the late 1700s, the first U.S. president, George Washington, was one of the first promoters of using cover crops to conserve soil in the Americas, and he often planted clover, grass, and buckwheat as cover crops (Groff, 2015). At the time, cover crops were mostly used in nutrient-depleted soils including monocultures of cotton in the southern U.S. and in other crops with limited residue input.

In the early 1900s, Hugh Hammond Bennett, known as the Father of Soil Conservation, vehemently advocated for the use of cover crops to reduce soil erosion, reduce nutrient leaching, and improve soil productivity during and in the aftermath of the Dust Bowl in his influential book "Soil Conservation" (Bennett, 1939). He considered cover crops as an integral piece to conserve soil and halt soil degradation. Indeed, Hugh Hammond Bennett was testifying before

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Congress in spring 1935 on the need to implement better soil conservation practices, such as cover crops, as a dust storm approached Washington, D.C. at the peak of the Dust Bowl. His testimony, coinciding with the dramatic arrival of the dust storm to the Capitol, facilitated the passage of the Soil Conservation Act by Congress and subsequent signing by President Roosevelt on April 27, 1935 (The National Agricultural Law Center, 1935). The Act specifically called for the implementation of soil erosion prevention measures such as growing vegetation (e.g., cover crops).

Cover crops were often used before World War II (1939–1945). Common cover crop species used by early adopters included crimson clover, field pea, crotalaria, sudangrass, millet, sweet clover, alfalfa, hairy vetch, winter rye, buckwheat, and others (Bennett, 1939; Lipman, 1912). Legume cover crops were used as sources of nutrients (e.g., N, C), while grass cover crops were used for erosion control. Following World War II, the rapid production and vast availability of commercial pesticides, herbicides, and synthetic fertilizers led to a slowed interest in the use of cover crops. Cover crop use was relatively minimal between 1940 and 1980 although organic farmers used cover crops throughout this period. However, increasing concerns over soil C losses, soil degradation, nutrient runoff, and nitrate leaching from agricultural lands contributed to reemergence of interest in cover crops in the 1980s.

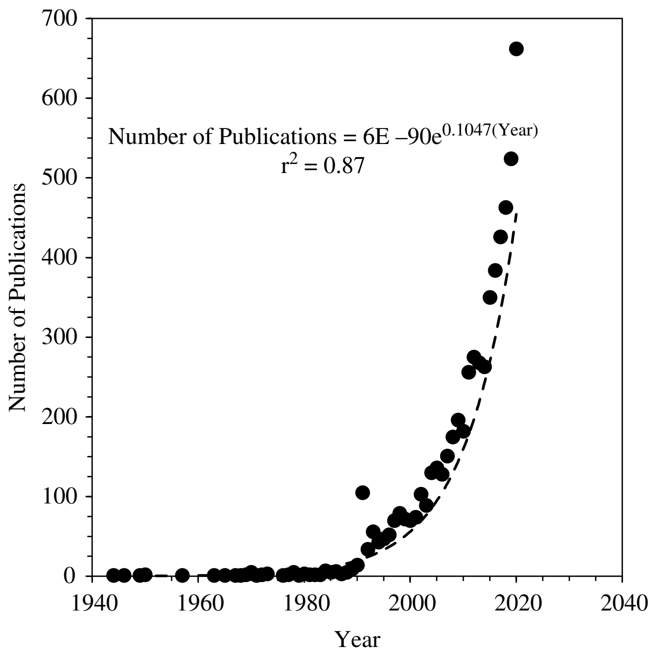

Figure 1.1 The number of publications on cover crops has increased exponentially in the past few decades. Web of Science.

The heightened interest in using cover crops in the past few decades resulted in an exponential increase in the number of publications (Figure 1.1). A search in Web of Science using the phrase "cover crops" up to December 2021, shows the number of publications was only 35 prior to 1980, 613 between 1980 and 2000, and 5967 between 2001 and 2021 (Figure 1.1). Most articles published before 1980 discussed the use of cover crops in low-biomass producing crops (e.g., cotton), orchards (e.g., cover crops planted under or between trees), and vegetable gardens for pest suppression (e.g., nematodes). Between 1980 and 2000, the main reasons for the use of cover crops were water and wind erosion control, soil fertility improvement, and the suppression of pests and diseases, while between 2000 and 2010, there was greater discussion of cover crops for sequestering soil C and improving soil quality.

Research on cover crops during the last decade (2010–2020) has expanded beyond the on-farm benefits from cover crop use. Now, most publications focus on ecosystem services or multi-functionality of cover crops, climate mitigation potential, agricultural intensification, soil biological environment, soil water management, and the challenges and opportunities of cover crop management. Also, several publications have recently emerged regarding the potential of cover crops to support livestock production via grazing or haying while improving farm economics and maintaining soil ecosystem services.

The above chronology indicates that while the use of cover crops is nothing new, interest in the multi-functionality of cover crops has increased in recent years (Figure 1.2).

Figure 1.2 No-till sunn hemp (left) and late-maturing soybean (right) summer cover crops in winter wheat-grain sorghum systems for enhancing soil ecosystem services. Blanco-Canqui et al., 2011; Photo by H. Blanco.

Most research on cover crops has been conducted in the U.S. Many studies are also evaluating management strategies to make cover crops work in water-limited environments where cover crop success can be restricted due to limited precipitation. Despite abundant literature, the adoption rate of cover crops is still slow. For example, in the U.S., cover crops are used in less than 5% of croplands although the adoption rate depends on the region. In some regions, cover crops are used in approximately 20% of croplands (Yoder et al., 2021).

1.2 Soil Ecosystem Services

Soils provide many invaluable services to humans (Figure 1.3). Not only do soils support food crops, but soils also support biomass as fiber for the textile industry,

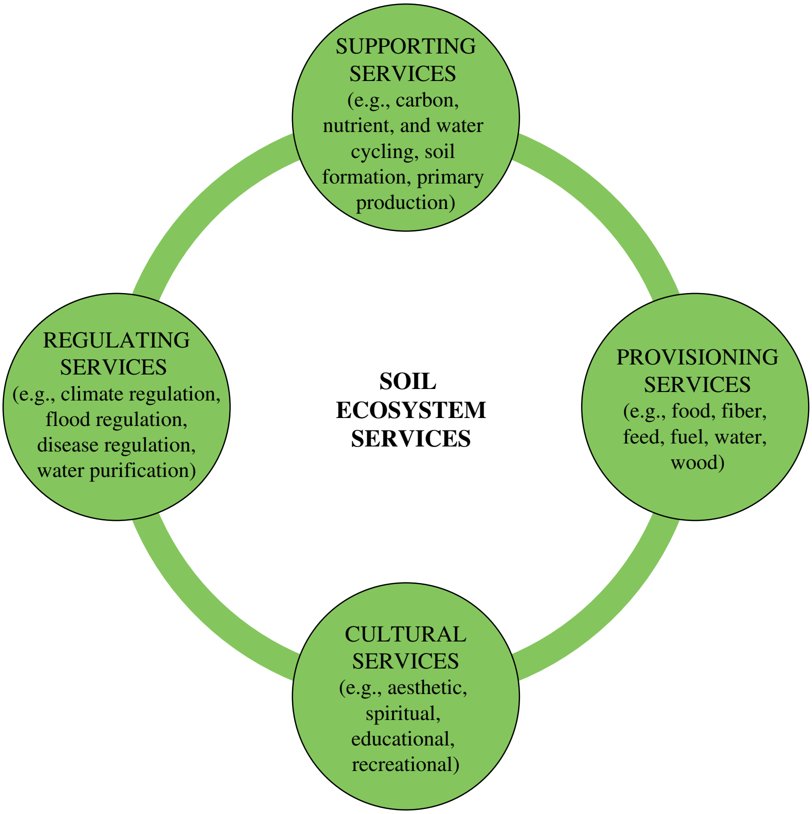

Figure 1.3 Soils provide numerous essential services. MEA, 2005; Dominati et al., 2010; Comerford et al., 2013.

feedstock for biofuel production, and forage for animals (Hatfield et al., 2017). Soils capture precipitation and irrigation water, clean water, degrade pollutants, sequester atmospheric C, adsorb and retain nutrients, moderate temperature, provide habitat for billions of soil organisms, and deliver many other services. These essential soil services can be grouped into four categories: supporting, provisioning, regulating, and cultural services (Figure 1.3; MEA, 2005; Dominati et al., 2010; Comerford et al., 2013). Supporting services refer to C, nutrient, and water cycling as well as primary production, soil formation, and microbial habitat, while provisioning services refer to the products we obtain from soil including water, food, fiber, feed, and fuel (MEA, 2005). Soils do not simply support and deliver products but also mediate and regulate many processes, which are vital to plants, animals, and humans (Hatfield et al., 2017). Such services are considered as regulating services and include climate regulation, air quality regulation, water movement and purification, prevention of floods, and management of pests and diseases (MEA, 2005). Also, soils have aesthetic, spiritual, educational, and recreational value, and these are grouped as cultural services (MEA, 2005).

The supporting, provisioning, regulating, and cultural services are all interconnected and subject to feedbacks among services. As an example, a soil may not be able to produce food and biomass if it cannot effectively cycle and recycle water and nutrients. Perhaps the leading service from the soil is the supporting service, which directly affects the capacity of the soil to produce food, fiber, feed, and fuel (provisioning services), buffer or moderate temperature, and contribute to water flow and storage (regulating services), improve landscape esthetics, and serve as recreational, educational, and spiritual space (cultural services).

The concept of soil ecosystem services is often implied but not entirely valued (Pires-Marques et al., 2021; Yee et al., 2021). Any service in society has a value. Thus, the services that soils provide have a value. Assigning a monetary value on different soil ecosystem services has been the topic of recent publications (Comerford et al., 2013; Mikhailova et al., 2021; Pires-Marques et al., 2021). Provisioning services such as food and biomass production can be easily valued because these products are marketable, but how about the rest of soil ecosystem services? For example, what is the monetary value of clean water, clean air, reduced C losses, reduced sediment losses, and other services?

Some have quantified the value of select soil ecosystem services by considering the “avoided cost” of soil erosion (Pires-Marques et al., 2021) and CO_2 emissions (Mikhailova et al., 2021), while others considered natural capita and flow of ecosystem services for the economic valuation of such services (Comerford et al., 2013; Yee et al., 2021). Comerford et al. (2013) reported some estimates of economic values for different ecosystem services including nitrate leaching, sediment loss, nutrient cycling, soil formation, salinization, contamination, and others. Most of these estimates are for supporting services. Also, available approaches often value a single service such as C sequestration or reduced losses of C as CO_2 (Mikhailova et al., 2021). However, linkages of a given service with related ecosystem service indicators need further consideration (Comerford et al., 2013). For instance, if a soil sequesters C or reduces CO_2 emissions, then soil aggregation or the amount of stable soil aggregates that contribute to the protection of C within aggregates should be considered during the valuation of services. This and other similar inter-related processes complicate the valuation.

Qualitative valuation of ecosystem services is relatively simple but quantitative valuation (monetary value) of ecosystem services is complex, especially when processes are interconnected or not directly marketable. A more comprehensive economic assessment of all indirectly marketable soil ecosystem services can help with decision-making process for the management of natural resources and thus ecosystem services. Indirectly marketable soil ecosystem services including recreation, spiritual fulfillment, landscape esthetics (e.g., year-round growing vegetation), mental and overall plant, animal, human health are often subtle but these soil services can be as valuable as marketable soil ecosystem services (Comerford et al., 2013; Yee et al., 2021).

The consideration of benefits from soil within the framework of ecosystem services is a holistic approach to view the soil as a service provider and one that deserves attention and care. Process-based models or quantitative frameworks are being developed to account for multiple soil processes contributing to a given service, although more refinement of such models is needed to fully quantify and value soil ecosystem services at farm-scales (Yee et al., 2021). It is clear that an understanding of the value of soil will be incomplete until we fully assign a quantitative value to each ecosystem service that soils provide. However, a value cannot be assigned until the impacts of cover crops on each soil service is quantified and understood.

1.3 Cover Crops and Soil Ecosystem Services

The concept of soil ecosystem services emerged in recent decades due to declining services from the soil and the need to improve, maintain, and restore such services (Figure 1.3). The fate and downfall of many past civilizations depended on the ability of soils to continuously deliver vital services to plants, animals, and humans (Bennett, 1939). Increased erosion (Thaler et al., 2021), increased water pollution (Haque, 2021), development of hypoxic zones (Anderson et al., 2021), and other environmental problems are current signs of accelerated loss of ecosystem services from soils (Table 1.1). This is particularly true under increasing extreme weather events with intense rainstorms, frequent droughts, extreme temperatures, and heat waves. Thus, the challenge of this century is to ensure that soil ecosystem

Table 1.1 Some of the Current Signs Showing Soil Ecosystem Services Have Declined

Decline in soil ecosystem services	Source
Increased losses of soil C via erosion, leaching, and as C emissions	Minasny et al., 2017; Jian et al., 2020
Reduced water quality or increased water pollution	Blanco-Canqui, 2018; Haque, 2021
Increased hypoxic and anoxic events in lakes and coastal areas	Fennel and Testa, 2019; Anderson et al., 2021
Increased susceptibility to water erosion (increased runoff and sediment loss)	Fenta et al., 2020; Thaler et al., 2021
Increased minimum and maximum temperature or temperature extremes	Kaye and Quemada, 2017; Zscheischler and Fischer, 2020
Increased susceptibility to prolonged and frequent flooding	Kaye and Quemada, 2017; Wright et al., 2017
Reduced soil and agroecosystem resilience against droughts	Vogel et al., 2019; Zscheischler and Fischer, 2020
Overall reduced health of soils against extreme events	Lehmann et al., 2020

services are maintained or improved not only to meet the demands for food, fuel, fiber, and feed but also to reduce water pollution, air pollution, soil C loss, soil erosion, and others. Soil ecosystem services are finite and exhaustible as the soil is highly dynamic and susceptible to rapid degradation when not managed properly. Management determines the ability or inability of the soils to provide the essential provisioning, regulating, supporting, and cultural ecosystem services.

One of the reemerging biological strategies that has potential to improve and maintain soil ecosystem services from agricultural lands is the inclusion of cover crops into current cropping systems (Figure 1.2). Unlike other management practices such as the introduction of perennial vegetation (e.g., grass hedges) to croplands, cover crops would not compete with land for food production as they are often grown during times when no crops are growing in the field. Even when cover crops are interseeded along main crops or before the main crop harvest, cover crops do not appear to compete with the main crops nor reduce crop yields under proper management. Interseeding cover crops via aerial broadcasting or drilling with improved high clearance equipment when main crops are in the field is a subject of current research (Blanco-Canqui et al., 2017).

The question is: Can cover crops under different scenarios of cover crop management improve or enhance all the ecosystem services that soils provide? If not, how can the potential of cover crops to deliver soil ecosystem services be enhanced? It is often considered that cover crops would improve soil properties, sequester C, and improve other ecosystem services. In some cases, this common belief may, however, contrast with field research data. Adoption and management of cover crops may not be free of challenges (Roesch-McNally et al., 2018). A need exists to better understand the extent to which cover crops can maintain or enhance the multiple ecosystem services of agricultural lands based on experimental data.

Furthermore, many recent publications are emphasizing the multi-functionality of cover crops (Schipanski et al., 2014; Blanco-Canqui et al., 2015; Finney & Kaye, 2017). For instance, grazing or harvesting cover crops is generating interest (Franzluebbers & Stuedemann, 2008; Kelly et al., 2021). However, can cover crops be grazed or harvested and still be considered cover crops? The existing definition of cover crops does not appear to account for some of the potential multi-functionality of cover crops such as supporting livestock production (SSSA, 2022).

This book discusses how cover crops affect the numerous ecosystem services that soils provide under different cover crop management scenarios and climatic conditions based on experimental data. It also highlights challenges and opportunities with cover crops to manage soil ecosystem services. The ecosystem services are discussed in terms of soil health, water erosion, wind erosion, greenhouse gas emissions, C sequestration, nutrient losses, soil water, weed management, soil fertility, crop yields, and economics, among others. It also includes discussion on how grazing or harvesting of cover crops could alter the main purpose of cover crops, which is soil conservation and management.

1.4 Summary

Interest in growing cover crops is reemerging as one of the options to address the decline in soil ecosystem services from agricultural lands. Soil ecosystem services refer to the numerous benefits we receive from soils. Soils not only produce food and biomass (marketable services) but also filter water, sequester C, recycle nutrients, suppress weeds and diseases, and moderate soil temperature, among other services. These services are grouped into four categories: supporting, provisioning, regulating, and cultural services.

Cover crops can be a strategy to restore, improve, and maintain these essential services from soil. The use of cover crops dates back over three millennia but slowed in the mid-1900s due to the advent of inorganic fertilizers, herbicides, and pesticides after World War II. Interest rapidly increased after the 1980s due to heightened concerns of water pollution (e.g., hypoxia, anoxia), soil erosion, soil C losses, frequency of extreme weather events, and others. In early years, cover

crops were primarily used for pest suppression and soil fertility improvement as green manure. Now, cover crops are being considered more and more as multi-functional systems that can deliver multiple soil ecosystem services. However, the potential of cover crops to function as multi-functional systems is not yet well understood. The question is: Can cover crop improve all soil ecosystem services? This book addresses this question based on experimental data on the impacts of cover crop management on soil environment, water quality, greenhouse gas emissions, C sequestration, soil water, weeds, crop yields, livestock production (e.g., grazing, haying), and other soil services.

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