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Regenerating Agricultural Landscapes with Perennial Groundcover for Intensive Crop Production

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Abstract: The Midwestern U.S. landscape is one of the most highly altered and intensively managed ecosystems in the country. The predominant crops grown are maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr]. They are typically grown as monocrops in a simple yearly rotation or with multiple years of maize (2 to 3) followed by a single year of soybean. This system is highly productive because the crops and management systems have been well adapted to the regional growing conditions through substantial public and private investment. Furthermore, markets and supporting infrastructure are highly developed for both crops. As maize and soybean production have intensified, a number of concerns have arisen due to the unintended environmental impacts on the ecosystem. Many areas across the Midwest are experiencing negative impacts on water quality, soil degradation, and increased flood risk due to changes in regional hydrology. The water quality impacts extend even further downstream. We propose the development of an innovative system for growing maize and soybean with perennial groundcover to recover ecosystem services historically provided naturally by predominantly perennial native plant communities. Reincorporating perennial plants into annual cropping systems has the potential of restoring ecosystem services without negatively impacting grain crop production and offers the prospect of increasing grain crop productivity through improving the biological functioning of the system.

Keywords: maize; soybean; perennial; groundcover; cropping system; crop breeding; crop diversity; intercropping; soil health; soil quality; ecosystem services; water quality; technology adoption; integrated pest management

1. Introduction

The Midwest U.S. is at the nexus of agricultural productivity, biofuel production, and water quality issues [1–3]. Situated almost entirely in this region, the U.S. Corn Belt is among the world's most productive agroecosystems producing nearly 40% of the world's maize (*Zea mays* L.) and over

25% of the world's soybean [*Glycine max* (L.) Merr]. The region produces most U.S. starch-based biofuels, and is home to the nation's first commercial cellulosic ethanol plants. However, intensive maize and soybean production have caused negative impacts on water quality and soil quality [4–7]. These impacts arise largely because the crops are present in the landscape for only a portion of the year, leaving the soil exposed to extended periods of wind and water erosion leading to nutrient loss, due to the susceptibility of bare soil [8]. Furthermore, the maize phase of the rotation requires large inputs of synthetic nitrogen fertilizer to be productive; yet the lack of actively growing root systems for more than half of each year means that much of the nitrogen fertilizer is lost to leaching. Cassman et al. [9] estimated that just 37% of the N fertilizer applied to maize in the north central U.S. is actually used by the crop. With climate projections predicting more droughts, floods, extreme rains, and other conditions in this region [10], eliminating the long periods of bare soil would greatly increase system stability and resiliency.

We propose a way forward—a perennial groundcover (PGC) approach—that involves recapturing some of the ecosystem services lost when the prairie was converted to agricultural landscapes. The PGC approach is predicated on increasing continuous soil surface cover through insertion of perennial plant species into annual cropping systems in ways that strategically alter surface hydrology to augment retention and infiltration of rain water and subsurface biology to enhance year-round nutrient retention and cycling. In essence, it is a landscape design approach inspired by the natural vegetation present prior to modern agriculture. A fundamental difference between the PGC approach and other approaches to conserving soil and water resources, is the effort to improve the highly-developed and productive maize-soybean system rather than replace it with alternative crops not as well adapted or developed to the region or restoring it to the original perennial landscape. Rather than underestimating the technological lock-in associated with existing practices and markets which can lead to solutions that are slow to deploy, or that are never implemented [11,12], our goal is to develop a functional system that sustains or enhances crop productivity, restores ecosystem services and protects the public and private investment that undergirds it. The proposed strategy is not one of replacement with alternative crops species, but rather one of augmenting the maize-soybean system to regenerate and recover ecosystem functions, particularly those with significant impacts on environmental outcomes.

2. Agricultural Context

2.1. The Landscape

Prior to European settlement, the dominant vegetation in the U.S. Midwest landscape was tall grass prairie, transitioning to hardwood deciduous forest to the east and mixed and short grass prairie to the west [13]. The native prairie was highly diverse, but as the name suggests was dominated by tall grasses throughout the more humid eastern reaches. The prairie plant communities evolved under intermittent defoliation by fire and herbivory and were relatively stable despite these disturbances. Since European settlement of the region began in the Nineteenth Century nearly all the native vegetation has been replaced by cultivated crops [14,15]. In Iowa, for example, almost 75% of native grasslands were converted to cropland by the middle 1800's, and nearly all of that land area is devoted to production of maize and soybean crops. Only small remnants of tall grass prairie exist today.

The agricultural landscapes that have evolved in this area are well suited to growing maize and soybean for a variety of reasons. They lay in a humid temperate climatic zone where precipitation is usually adequate to meet water requirements of the crops, and winters are severe enough to break pest cycles that plague production in warmer southern climates [16]. The Mollisol soils predominant in this region formed in recently deposited glacial till, loess, or fluvial parent materials under prairie vegetation. Thus they are generally deep and rich in organic matter making them inherently fertile and productive [17]. However, much of the soil organic matter that was present under native vegetation has been lost due to erosion and accelerated oxidation as a consequence of modern agricultural practices [18–20]. Current soil organic matter levels are about half of what they once were under prairie vegetation (Figure 1) [21].

Figure 1. Comparison of soil developed under continuous prairie vegetation (**a**) and an adjacent soil (**b**) under decades of continuous cultivation. The profiles visually illustrate the loss in soil structure incurred from repeated tillage and the consequent loss in soil organic carbon. The undisturbed soil is richly aggregated in the upper 0–20 cm A-horizon, whereas the cultivated soil has a shallower depth of the A-horizon that is lighter in color, and has less aggregation. Photo: David Laird.

The wholesale conversion of land from native vegetation to crop production created numerous environmental problems that are becoming more pronounced as crop production intensifies [14]. While native grasslands were dominated by perennial species that provided continuous cover to the land surface and extensive root systems that helped to build soil organic matter levels, modern agricultural systems depend on the production of relatively few species that occupy it for less than half of the year. Consequently, the soil receives less organic carbon (C) inputs and the soil surface is exposed to the elements and extensive erosion has occurred throughout the region [22]. Some of this eroded soil ultimately ends up in surface water where it causes sedimentation and increases turbidity. This soil, carrying with it agricultural chemicals and nutrients, can be a major source of pollution [23,24]. Installation of extensive sub-surface drainage systems to drain excess water from what were once prairie wetlands has increased the movement of mobile nutrients and chemicals, bypassing the natural filtering process of percolating through the soil profile. In contrast, nutrients in native plant communities were efficiently captured by the extensive root systems of perennial plants and recycled into plant biomass. Thus, native prairie systems were relatively closed systems, with little movement of nutrients from prairie soils into surface or ground water [25].

2.2. The Crops

Maize and soybean are grown throughout the U.S. with commercial production concentrated in the North Central states, an area often called the Corn Belt. Given the preponderance of soybean produced in short rotation with maize the area has lately been referred to as the corn-soybean belt [26], but it is nonetheless predominantly mono-cropped. The region is slowly expanding to the north and west as improved germplasm and management practices are being developed to overcome climatic constraints [27]. Furthermore, evidence exists that the climate in this region is becoming more amenable to maize and soybean production as a consequence of climate change [28].

Ten Midwestern states account for over 80% of U.S. maize production, with the top five (Iowa, Illinois, Nebraska, Minnesota, Indiana) accounting for over 60% [29]. In the most recent growing season, total acreage planted to maize was estimated at 37.1 million ha with 33.9 million ha, harvested for grain [29]. Soybean was planted on nearly as many ha and 33.5 million ha (90%) were harvested. Overall, these two crops together accounted for US$ 89.5 billion in 2017, with maize accounting for 79.6% of the value of grains produced and soybean for 91.9% of the value of oilseeds [29].

Given the importance of these two crops to the agricultural economy, and the huge investments in crop development and support infrastructure, a rational approach to solving environmental problems associated with their production would be to develop better management practices with lower impacts on the environment. Attempts to replace them with alternative crops which lag decades in commercial development, lack adequate markets and infrastructure, and are therefore less profitable to produce on any realistic scale, are unlikely to succeed within a reasonable timeframe. Environmental problems associated with maize and soybean production are the result of the ways in which these crops are grown, not the crops themselves. The most straightforward and economically realistic approach to achieving better environmental outcomes is to develop improved production practices that have fewer negative impacts.

2.3. Biofuels

As required by the Energy Independence and Security Act of 2007, the U.S. set a goal of producing 136 billion L y^{-1} of renewable fuel by 2022, with 58% or 79.5 billion L y^{-1} to be in the form of advanced biofuels [30]. Achieving this goal will require focused and substantial changes in how agricultural landscapes are designed and managed because agricultural residues and dedicated energy crops are projected to account for most of the needed biomass for producing this renewable fuel [31]. Furthermore, to meet the specific cellulosic fuel requirement of 61 billion L y^{-1}, 20 to 30% of the cellulosic feedstock will likely be comprised of maize stover [32]. This aspect is reflected by the predictions in the U.S. Billion-Ton Update indicating that the majority of biomass available within the North Central Region will be derived from crop residues, predominantly maize stover [31]. The U.S. is unlikely to reach its goal of displacing 30% of 2005 petroleum consumption without tapping into this maize stover residue reserve as this is the largest readily available source of biomass at present and is projected to remain so well into the future.

However, serious concerns have been expressed regarding negative and in some cases potentially devastating environmental consequences of indiscriminately harvesting crop residues [33,34]. Crop residues are generally returned to the field where they provide soil cover throughout the intervening fallow period between successive crops by creating a barrier to reduce wind and water erosion. Returning crop residues to the soil recycles nutrients and adds carbon, which is critical for building soil organic matter, maintaining soil structure and enhancing nutrient cycling [35]. Hence, crop residues provide important ecosystem services that protect and enhance soil quality and off-farm water and air quality [36].

The amount of maize stover that can be removed from a field without adversely affecting these services depends on a number of factors. Land that is highly susceptible to erosion due to sloping topography needs more surface residue than level ground and maintaining soil organic matter requires even more residue return than protecting the soil from erosion [37]. Estimates indicate that on average, only about 40% of the maize stover that is produced within the North Central U.S. region can be safely harvested when conventional crop management systems are used [38]. Therefore, it is critical that novel management systems are developed to enable sustainable removal of maize stover [39]. To meet the projected biomass demand, alternative cropping systems that reduce the vulnerability of land to environmental degradation must be developed and implemented [33]. Incorporating the PGC approach in maize production systems would allow removal of crop residue by minimizing negative effects on soil and water quality.

3. Environmental Concerns

3.1. Nitrogen Efflux and Water Quality

Less than 40% of the N fertilizer applied to maize fields in the Midwest is actually used by the maize crop [9,21,40]. The rest is either leached from the soil as NO_3^-, contaminating surface and ground water, or is volatilized to the atmosphere as NH_3 (contributing to air pollution), N_2 (harmless), or N_2O (a potent greenhouse gas). These N losses are a large, but unaccounted for economic cost to farmers, cause serious water quality problems, impact recreational use of water, and contribute about 2.5% of total U.S. greenhouse gas (GHG) emissions. Nutrients leaching from maize and soybean fields are the leading cause of impaired water quality of groundwater, rivers and lakes throughout the U.S. Midwest [41,42]. Further, flow-weighted concentrations and fluxes were found to have increased at sites within the Mississippi River Basin (MRB) between 1980 and 2008 [43]. Nutrients, including N and P flowing down the Mississippi River and into the Gulf of Mexico from Midwestern farms, are the leading cause of the hypoxic zone, a.k.a. "dead zone" in the Gulf of Mexico, an area where the concentration of dissolved oxygen in the water has decreased to a level that can no longer support marine life [44,45]. In 2017, NOAA estimated the size of the hypoxic zone to be 22,730 square kilometers (8776 square miles); the largest area measured since hypoxic zone mapping began in 1985 [46]. New and innovative management practices are critically needed to meet the EPA goal of reducing NO_3^- loads in the Mississippi river by 45% [47,48].

One of the factors contributing to the high nitrogen export from the Upper MRB in particular is that the high soil nitrogen availability occurs not only during a period of insufficient crop nitrogen uptake, but also during a wet time of the year when farmers generally want to accelerate the draining of their land so that field operations can begin [49]. In areas where soil moisture content is high during the early spring and summer, it is common to use subsurface tile drainage to allow water above field capactity to exit the field more rapidly than natural drainage alone. This not only improves field trafficability, but prevents waterlogged soil conditions that can decrease crop yield. An estimated 16 million hectares in the Corn Belt have subsurface tile drainage, according to one estimate, with some areas particularly in Iowa and Illinois having subsurface drainage tiles beneath 60–80% of farmed acres [50]. This estimate is likely low, because it was based in large part on data published in 1987 and 1992. An analysis of continuous monitoring data from the Otter Creek watershed in Northeast Iowa, confirmed that tile drainage was a greater threat to stream nitrate loads than groundwater or surface quick-flow sources [51]. Other predictive models using actual N input and landscape data also implicated tile drainage in the nitrate loading observed in the UMRB [52]. The installation of these extensive tile drainage networks, done to improve agricultural productivity, has altered the hydrology of these agricultural watersheds [53]. Innovative management practices therefore will need to pertain to tile-drained landscapes to have the most widespread applicability and impact.

3.2. Soil Erosion

Accelerated soil erosion is the most widespread soil degradation process not only in the Midwest, but throughout the world. Soil erosion results in loss of effective rooting depth, decreased soil fertility, downstream pollution of receiving water bodies, and increased emission of greenhouse gases from soils [54,55].

In the North Central U.S., conventional production of annual row crops means that for a significant part of the year between harvest in mid to late fall and partial canopy closure in early summer, there is no substantial ground cover. Furthermore, because the crops are grown in rows, even when the vegetation is robust, bare soil still exists between the crop rows. Combined with the damaging effects of tillage, the result is intolerable rates of soil erosion by water on cropland that are an order of magnitude larger than erosion rates on land enrolled in the Conservation Reserve Program (CRP) and restored to non-working grassland (Figure 2).

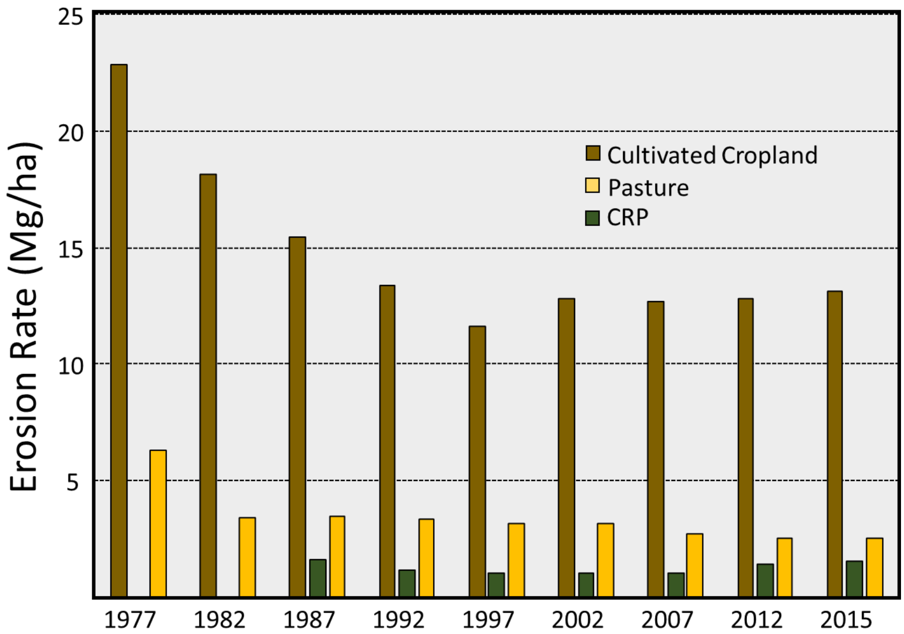

Figure 2. Estimated average annual sheet and rill erosion by water for the state of Iowa, according the USDA National Resources Inventory [56].

While soil erosion on cropland in Iowa, for example, was reduced by almost 50% between 1977 and 1997, there has been virtually no significant progress since that time. Indeed, there has even been some increase in estimated erosion rates from the low in 1997. Furthermore, while Figure 2 shows the average values across the state, there is significant spatial and temporal variability (Figure 3), such that some watersheds experience annual erosion at rates many times higher than the statewide average. Pressures to use crop residues, which otherwise would buffer the soil against erosive forces, to meet biomass demands for biofuels production will only exacerbate the current problems. Additionally, increases in the volume and erosive power of rainfall expected in the Midwest under a changing climate will likewise worsen the rates of soil loss [57].

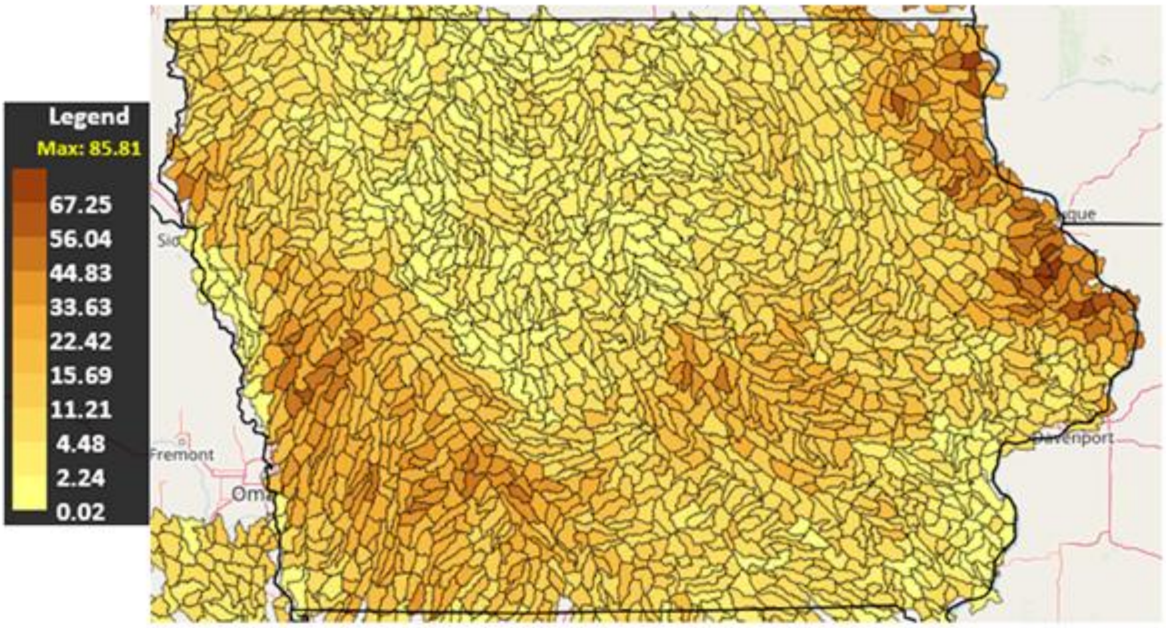

Figure 3. As an example, estimated annual soil loss for the 2017–2018 water year across Iowa, illustrating erosion rates from 3 to more than 70 Mg/ha. The latter corresponds to an erosion rate of roughly 6 mm (0.2 inch) of soil loss in four years. Figure courtesy of the Daily Erosion Project (www.dailyerosion.org).

The negative consequences of high rates of erosion are numerous and substantial. To the farmer, soil erosion poses a risk to sustained crop production by reducing soil depth and quality. A potentially more immediate concern is that erosion generates sediment, which is a water quality pollutant. As explained by Nearing et al. [58], the downstream costs of sediment delivery include stream degradation, disturbance to wildlife habitat, flooding, and direct costs for dredging, levees, and reservoir storage losses. Furthermore, eroded sediments carry soil bound chemical contaminants, such as phosphorus and certain agricultural chemicals, to receiving water bodies.

Any soil management practice that reduces soil disturbance and provides more surface cover reduces the risk of soil erosion and transport, thereby reducing the damage this process can cause. Increasing the percent of the soil covered by robust vegetation—both the proportion of the field with ground cover, and the proportion of the year with ground cover—would reduce soil erosion rates considerably.

3.3. Soil Quality and Ecosystem Services

Soil supports plant production, which is the foundation for the human food web as well as the raw material or feedstock for plant-derived bio-products and biofuels. Soil is a living environment that hosts about a quarter of our planet's species. It is a rich source of pharmaceuticals and genetic resources. Soil has important functions of storing and regulating the cycling of the water and chemical elements. As water passes through the soil profile, it filters and cleans the water; it detoxifies potentially toxic compounds including heavy metals and xenobiotics. Soil also serves as the primary terrestrial carbon pool, storing about three times more carbon than exists in the atmosphere or terrestrial vegetation. Thus, soil plays a key role in regulating greenhouse gas emissions and subsequent climate change effects. Soil has cultural, spiritual, aesthetic, archaeological and educational roles that are an essential part of human life unrecognized by most people.

In 1993, the National Academy of Sciences issued a report that stimulated public discussion regarding soil and water quality [59]. The report was among the first policy-oriented publications emphasizing that healthy soils are vital for sustained agricultural production to support an increasing global population. It identified several factors contributing to soil degradation including erosion, compaction, salinization, soil organic matter loss and diminished biological activity. Unfortunately, more than two decades later soil degradation continues to be a global problem [60].

Recognizing that loss of soil organic matter disrupts several critical soil functions including nutrient cycling, microbial food sources and community structure, aggregate stability, hydrology, and overall productivity, investment focused on understanding how soils function has increased exponentially since 2012. It has been proposed that erosion-induced CO_2 emissions can contribute to GHG emissions [55], but others show erosion might result in a net sink for atmospheric CO_2 [61]. More important, however, might be erosion-induced losses of other ecosystem services—nutrient-supplying power, water infiltration and retention, and overall enhanced plant growth. Disaggregated soil particles can be more easily mobilized by forces associated with water or wind erosion and/or tillage operations [62], with subsequent deposition into low or depression sites within landscapes [63,64], or worse, mobilized and lost from the farm [65]. As a result, productivity in both eroded and deposition areas is not only reduced, but also those sites have increased potential for nutrient leaching and/or denitrification which can negatively affect water and air quality. Conventional maize-soybean production has led to declines in soil organic matter (SOM), due to erosion, insufficient carbon input, excessive crop residue removal, tillage, or poor drainage (Figure 4). Ultimately, this decline can result in decreased productivity and increased potential for water quality degradation. However, adopting agricultural practices that restore SOM has the potential of reversing this trend.

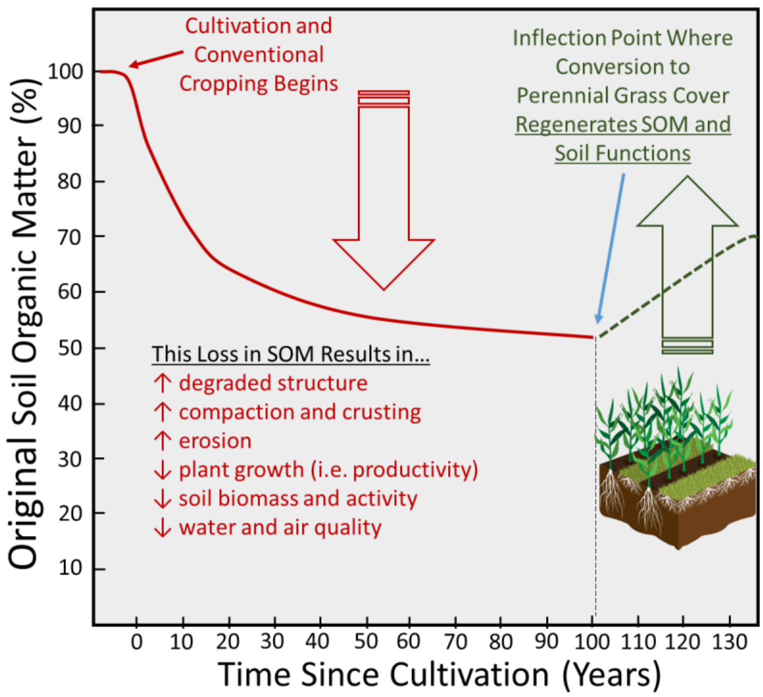

Figure 4. A conceptual diagram illustrating how loss of soil organic matter leads to soil degradation with ultimate outcomes of reduced productivity and increased potential for water quality impairment. PGC systems will increase soil organic matter and regenerate the productive capacity of the soil. (Adapted from Weil & Brady [66]).

4. Mitigating Environmental Impacts of Crop Production

4.1. Annual Cover Crop Systems

Restoring perennial vegetative cover to the agroecosystem can be achieved using annual plant species grown in a relay cropping system [67]. A commonly used cover-crop system employs a summer annual grain grown in sequence with a winter annual grain. The use of annual cover crops grown in a relay system with maize has been extensively researched and the potential benefits of doing so are well documented [68]. Winter annual cover crops planted in the fall afford several positive impacts. They immobilize NO_3 and thereby decrease its leaching through the rooting zone into groundwater and tile drains [69]. They prevent erosion by dampening the force of rainfall [36], reduce above ground water flow rate, decrease runoff, and increase infiltration of water into the soil [70].

Establishment of annual cover crops following maize is often challenging especially in the northern reaches of the Corn Belt [67]. Planting of cover crops generally occurs after maize harvest when weather and soil conditions are often not conducive to establishment of the cover crop [68]. Therefore, establishment of winter annual cover crops following maize and soybean is somewhat inconsistent and carries a relatively high risk of failure. Interseeding the cover crop into a standing maize crop is one way to overcome the weather constraint, but requires aerial seeding, which is expensive and limited by the number of available aircraft and operators.

Winter annual cover crops must be terminated in the spring to allow for field preparation and planting of the primary summer annual grain crop. The timeliness of these field operations can be delayed by weather and wet soil conditions. Delaying planting of the grain crop has a negative impact on its yield and reduces overall productivity. In some growing seasons, there is ample time to terminate the cover crop and complete field preparation in time to maximize growth of the grain crop. Even so, growing a winter annual in sequence with a summer annual grain greatly complicates management of the primary crop and frequently reduces its productivity, especially maize [71,72]. Some annual cover crops, including winter rye (*Secale cereal* L.), can negatively impact yield of the subsequent maize crop [73] by increasing root pathogens [74,75].

Annual cover crop establishment, successful or not, incurs significant costs in time and money that cannot be reliably recovered through either improved productivity of the primary crop or market value of the cover crop itself [76,77]. A recent survey of Iowa farmers indicated that economics are a barrier, particularly "pressure to make profit margins makes it difficult to invest in conservation practices," yet 35% of the respondents had increased or adopted cover cropping practices suggesting that such barriers, while real, are not insurmountable [78]. Additionally, the use of cover crops may be precluded by complex management requirements related to cover crop termination and uncertainty of impacts on crop insurance [79,80].

4.2. Perennial Groundcover

A promising alternative to a relay cropping system is intercropping with a perennial groundcover. The system achieves perennial soil cover and the associated benefits by year-round presence of the groundcover. Unlike annual cover crops, perennial groundcovers do not need to be replanted or terminated every year. They can coexist as a companion crop with maize throughout its growing season, thus providing ecosystem services throughout the year. Using strip tillage to create and manage zones where maize was planted, and nutrients were applied and incorporated, Wiggans et al. [81] demonstrated that high-yielding maize could be produced in central Iowa with perennial groundcover. In two out of three growing seasons, maize planted into perennial groundcover produced equal yields as that grown conventionally (Figure 5). In a fourth year of the same study, maize planted into perennial groundcover out yielded conventionally grown maize [82] (data not previously published). Obtaining these yields required chemical suppression of the groundcover in spring which at present is necessary to prevent eliciting a shade avoidance response (SAR) in juvenile maize [83,84]. While careful management of competition between the perennial groundcover and maize was needed, these results were achieved using maize hybrids and groundcovers that had been developed for other uses and were not optimized to work together. The use of incompatible perennial grass can result in decreased yields of maize [85] and soybean [86]. Developing maize hybrids and soybean and groundcover varieties specifically designed for perennial groundcover systems, however, would likely result in significant performance increases for this system.

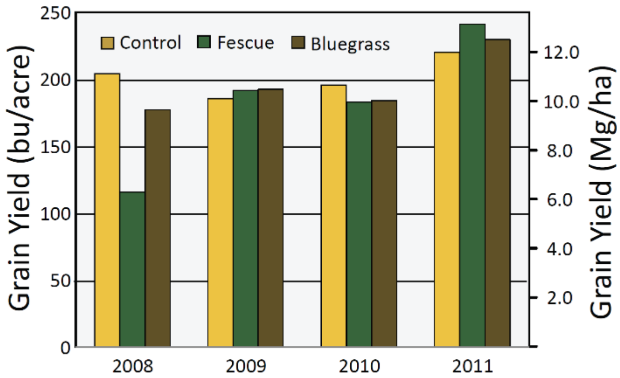

Figure 5. Grain yield in four successive growing seasons for maize grown conventionally (Control) and with perennial groundcover (red fescue, Kentucky bluegrass) in central Iowa, USA.

Others have demonstrated that perennial groundcover can be suitable for grain production systems. In southern Illinois, U.S., maize grain production ranged from 5.7 to 10.8 Mg ha^{-1} when grown in perennial grass sods when the grasses were managed with various herbicides [87]. Perennial grass cover following harvest ranged from 0 to 87%. Conversely, yield of maize planted in living alfalfa (*Medicago sativa* L.) ranged from 8.0 to 16.4 Mg ha^{-1}, but persistence of the alfalfa was poor to nonexistent. Soybean production with tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.) ranged from 3.0 to 3.6 kg ha^{-1} while grass persistence ranged from 21 to 83% cover after harvest. Greatest soil cover at harvest for grasses was with strip tillage and paraquat applied to the grass, however, this practice resulted in lower soybean yields than in other systems that had less grass cover at harvest. In a separate study [88], maize grain production in a tall fescue sod ranged from 0.7 to 8.6 Mg ha^{-1} depending on the herbicide program. Tall fescue biomass at maize harvest ranged from 1.6 to 6.1 Mg ha^{-1}.

In Georgia, U.S., maize planted in wider 90-cm rows compared with 75-cm row width with 20-cm wide herbicide bands of dead white clover (*Trifolium repens* L.) was a suitable living mulch treatment [89]. Successful living mulch systems with white clover were capable of meeting a substantial portion of maize N needs [90]. Conversely, utilization of seven different perennial legumes averaged N fertilizer equivalency of 13 to 71 kg N ha^{-1} yr^{-1} at 0 N rates [91] in comparatively lower maize yielding environments.

An important distinction between these other approaches to intercropping grain crops with perennial groundcover is that in the system we envision the primary purpose of the groundcover is to impart ecosystem services. The grain crop remains the principal economic crop and improvements derived from the groundcover accrue from contributions that improve grain crop productivity. The groundcover is not intended to be harvested and marketed, and thus can be developed to fill ecosystem gaps created by high-yielding grain and oilseed crops. Perennial groundcover varieties that are adapted to the growing environment will significantly curtail soil erosion by extending the duration of vegetative soil cover year around. Additionally, by attenuating the impact of rainfall and interrupting surface runoff, they will increase water infiltration. During semi-dormancy in summer, they can serve as a barrier to evaporative losses increasing the soil moisture available to the growing grain crop [92]. By increasing moisture retention and impeding its loss, perennial groundcover could indirectly provide critical moisture to the grain crop, particularly during dry periods.

In the U.S. Midwest, perennial groundcover varieties begin growth in spring well before grain crops are planted. During this period when soil is warming and biological activity is increasing, the groundcover will actively immobilize soluble nutrients including nitrate mineralized from soil organic matter. By doing so, they decrease contamination of ground and surface waters during the period of the year when nitrate levels in surface waters generally peak [49,93]. Simultaneously, they will increase nitrogen use efficiency by retaining N that would have been lost. By building soil organic matter through reduced tillage and root growth, perennial groundcover will contribute to increased retention of other nutrients through immobilization and by increasing soil cation exchange capacity.

Beyond the attributes inherent from a perennial growth habit, groundcover varieties with enhanced traits could be developed to further extend their benefits. All of the traits already mentioned could be amplified and additional ones could be developed. For example, biological nitrification inhibitors have been identified in the root exudates of several grass species [94,95]. These compounds disrupt the conversion of ammonium to nitrate by soil microbes. Since ammonium ions are retained better by soil, this trait could improve the performance of the groundcover in mitigating nitrate leaching. Several candidate groundcover species are known to associate with endophytic fungi that produce allelochemicals that have antibiosis properties against other organisms [96,97]. Novel endophytes that produce defensive chemicals against diseases and insects could be developed for perennial groundcovers as part of a pest management strategy for maize and soybean production.

5. Designing and Developing Perennial Groundcover Systems

Designing a system for growing grain crops with perennial groundcover will require a well-coordinated and multidisciplinary approach. It will involve carefully constructing a crop ecosystem that optimizes growth of the crop and groundcover in time and space to achieve increased production concurrent with enhanced ecosystem services. Doing so will necessitate the development of agronomic practices that minimize competition between the crop and groundcover and amplify the environmental benefits of providing perennial cover. It will require developing crop and groundcover varieties that are spatially and temporally compatible. Much of the potential for increasing crop productivity lies belowground. Understanding how perennial groundcover influences soil water and nutrient retention will be critical for leveraging these effects for improvements in short- and long-term production. Understanding broader-scale impacts on the environment and how they might relate to landscape management is also important to deploying PGC systems where they will provide the most benefit. Finally, the adoption of a system will depend on economic and sociological factors that determine acceptance by producers and agricultural industry. All of these activities must be coordinated to achieve successful development and commercialization of a PGC system.

In much of the world, large-scale crop production is a complex, technological undertaking, bounded by biological and climactic realities, and driven by market and regulatory forces [98]. To mitigate the financial risks inherent to farming, farmers and the agricultural industry that supports them have a natural preference for simple strategies that overcome spatial and climactic variability. A challenge and opportunity of the PGC vision is its reliance on two primary cultivated organisms: the annual cash crop and the perennial groundcover. The opportunity has been detailed elsewhere in this paper, but briefly is based upon the multiple ecosystem services provided by the perennial cover and the relative simplicity of maintaining that perennial cover compared to annual cover crops. The challenge comes from the significantly greater complexity of such a system, which now has variability along each dimension of interaction between the two crops—e.g., rooting habits of each species, spectral reflectance of the groundcover and spectral sensitivity of the cash crop, and soil preparation methods. Handling this complexity can be accomplished by applying systems engineering principles—i.e., by formally considering the interconnections between key subsystems in the development of the overall system [99]. In the case of PGC, this means explicitly identifying the critical dimensions of interaction, and then considering those interactions at each stage of the development process. It also means identifying key performance indicators (or in systems engineering terms, Measures of Performance), recognizing the bounds of those indicators, and regularly evaluating the system on those values to track and guide the development of the system [100].

As described previously (Section 4.2, Figure 5), multi-year small-scale trials in one location have validated the claim that PGC maize can provide competitive or better yields. While some early adopters may be willing to trial small parts of their fields based on such evidence, there are inherent risks associated with using a PGC-maize approach at this time, because the system has not been sufficiently tested. Research and development efforts in agriculture and beyond focus on reducing the risk and cost of new approaches, and the rapidity with which they are successful in de-risking impacts the time-to-market. Würschum et al. [101] described a citizen-science approach to a soybean experiment that recruited over two-thousand persons thereby greatly increasing the geographic range and total number of experimental treatments in a breeding experiment. Cooperating with producers, a citizen-science approach could profoundly accelerate the rate of knowledge generation by increasing the number of evaluations and the geographical area covered. Equally important, working with producers in this context leverages the significant human capital—in the form of technical expertise—in the population of producers, and simultaneously decreases the unit cost of experimentation.

5.1. Crop Ecology and Management

Coexistence of multiple plant species growing in association within natural plant communities is the norm rather than an exception. Maintaining a monoculture usually requires substantial effort to modify the growing environment to suit the needs of a single plant species. In addition to providing nutrients, managing water, and modifying the soil environment through tillage, herbicides and other biocides are needed to check encroachment of other species. The goal of such management practices is to create a near optimum growing environment for the crop plant in order to maximize yield. In natural plant communities, not all biological interactions are negative for the organisms involved and indeed some are neutral and others are positive [102]. There are many examples of commensalism and mutualism in natural plant communities [103,104]. Conceptually, designing a simple plant community that positively affects crop yield and provides ecosystem services related to environmental quality, and pest suppression is possible. For instance, crop diversification using intercropping can potentially reduce weed population density and biomass production compared to monocrops [105]. This natural weed suppressive ability is most likely based on varying levels of resource competition, allelopathy, or weed seed predation/microbial decay provided by the intercrops that can create an unstable environment to prevent weed population shifts to a particular species, which is an increasing concern in mono-cropped maize or soybean.

5.1.1. Minimizing Interspecific Competition

Interspecific competition among plants seldom ends well for one or both species involved. The more competitive species will out-compete the other for available resources resulting in exclusion of the other or coexistence with growth of both species diminished by the other. Competition between the species in PGC systems needs to be avoided to ensure optimum crop performance and persistence of the groundcover and its beneficial effects. Plants have adapted a number of mechanisms for coexisting in communities. One widely accepted mechanism for minimizing competition in natural plant communities involves differential adaptation to niches in the growing environment [106]. Niche complementarity involves spatial and temporal localization of resource acquisition so that species do not compete directly. The greater the number of niches available, the greater potential diversity of the plant community there will be. Crop and soil management is traditionally directed at homogenization of the growing environment. Niches are overcome or destroyed by providing resources that would otherwise be limiting. This strategy ensures that the crop plant will be the most competitive and dominant species across a field.

A reasonable approach to developing PGC systems would be to manage the crop environment to provide separate niches for the crop and perennial groundcover. Growth of the latter could be restricted to a relatively smaller volume of soil and to a time period that is asynchronous to maximum growth of the crop (Figure 6). The space and time occupied by crop and the groundcover should be as different as possible. Ideally, the groundcover species should be low growing and occupy a smaller and shallower volume of soil than the crop. Its optimum growth temperature should be different than that of the grain crop so that its maximum demand for resources occurs at a different time. For maize and soybean production, the groundcover species should grow actively in the spring and autumn and ideally go dormant during summer when growth of the crop reaches its maximum. An effective groundcover would also need to persist through periods of low available moisture under shade, recover and begin active growth as daily temperatures decline and the grain crop matures and dries down. After harvest of the grain, the groundcover needs to provide enough soil cover to arrest erosion and have sufficient hardiness to survive the winter.

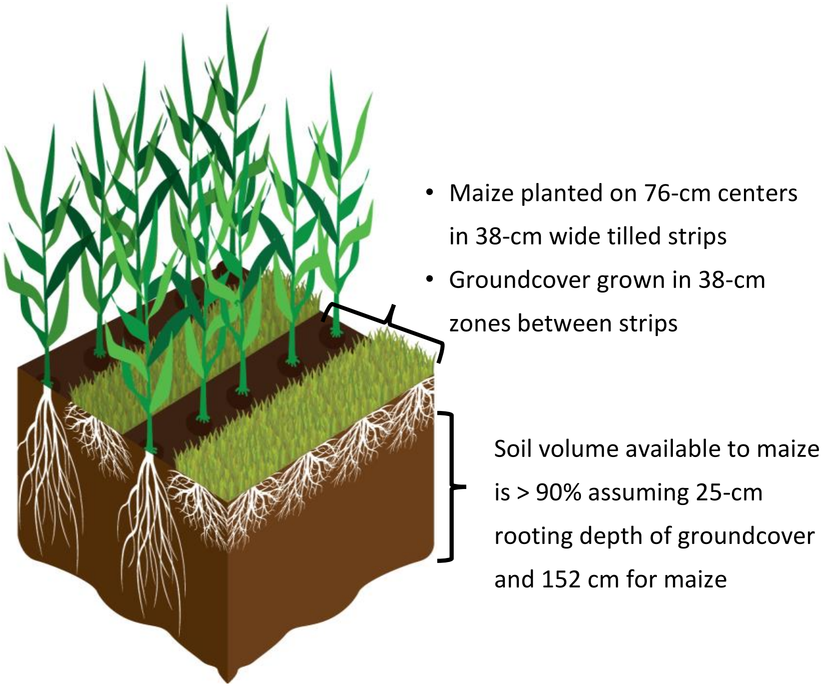

Figure 6. Profile of established maize growing with perennial groundcover. In this configuration, maize is planted into 38-cm tilled strips alternating with 38-cm wide strips of perennial groundcover. Base groundcover is 50% providing resistance to surface water flow, increased infiltration, and decreased soil erosion. Belowground, the groundcover occupies less than 10% of the soil volume reserving over 90% for the grain crop to exploit. Management practices should be designed to maintain localization of the two species in time as well as space to ensure minimum competition and optimum grain production. The ideotype for a perennial groundcover is cool-season growth (spring and fall), summer dormancy, a shallow root system, rhizomatous or stoloniferous regrowth, shade tolerance, and winter hardiness.

5.1.2. Species Complementarity

Flynn et al. [107].evaluated thirty-five potential groundcover species for continuous maize production. The trial was designed to identify species with minimal negative associative effects on maize yield. Strip tillage was used to create zones for planting maize, but no other groundcover suppression strategies were used. They identified several species that could be suitable candidates as perennial groundcovers for continuous maize production. These included some of the bluegrasses (*Poa* spp.), fine leaf fescues (*Festuca* spp.) and bentgrasses (*Agrostis* spp.) [107].. Common to all these species is that they are cool-season grasses with the C3 photosynthesis system, a relatively shallow root system, good shade tolerance, excellent recuperative capability and fall regrowth, an optimum growth temperature < 25 °C and are sufficiently winter hardy. Thus, their growth complements that of maize which has C4 photosynthesis, a deeper root system and higher optimum temperature for growth (>30 °C). The contrasting and complementary characteristics between the cool-season groundcovers and maize afford the possibility for them to coexist in a perennial groundcover system. The study by Flynn et al. [107] was designed to screen potential groundcover species and their competitive effects on maize grain yield. Thus, groundcover species had a negative impact on yield when not suppressed in the spring. Even the least competitive groundcover species reduced maize yield by 23% when not suppressed.

5.1.3. Managing Competition

Even when competition between the crop and groundcover is minimized by compartmentalizing the growing environment, residual competitive effects remain [107]. These are observed most acutely during establishment of the crop when growth of the groundcover is near its maximum rate. During this period the presence of the groundcover alters the growth and development of the crop in a manner similar to the response observed when establishing in the presence of weed species. These effects are not easily attributed to any direct competition between the species for resources because there is physical separation of the seed from the zone of groundcover growth. They are generally observed even when there are no obvious limitations due to shade, soil moisture or nutrient status.

While acknowledging resource competition between more aggressive groundcovers and maize, Flynn et al. [107] suggested that the SAR by maize likely plays an important role in reducing yield when it is grown with less competitive groundcovers. Shade avoidance is triggered by a reduction in red:far red light associated with increased absorbance of red light by the actively growing groundcover. Mediated by a phytochrome response, maize senses potential competition and alters its growth to avoid it [108,109], a response that occurs similarly in other species [110]. As a consequence, stem elongation accelerates and leaf development is somewhat retarded [111,112]. Grain yield is reduced because SAR is often associated with lower seed set. This conjecture is yet to be definitively proven, but it explains many of the observed effects when maize is grown with less aggressive groundcovers. If real, it provides scope for reducing the need for chemical suppression of the groundcover by developing groundcover varieties that go dormant early in the growing season. Genetic variation among maize germplasm for sensitivity to red:far red light should allow development of elite hybrids that are insensitive to the presence of a groundcover. These, however, are long-term strategies for mitigating SAR and for the time being groundcover suppression will be necessary to prevent triggering SAR by developing maize plants.

Wiggans et al. [81,92] evaluated groundcover suppression strategies for no-tilled and zone-tilled maize grown in Kentucky bluegrass (*Poa pratensis* L.) and red fescue (*Festuca rubra* L.). Suppression strategies included pre-plant burn down with paraquat (*N*,*N*′-dimethyl-4,4′-bipyridinium dichloride) followed by post-emergence glyphosate (*N*-(phosphonomethyl)glycine) in either one or two applications. A wet spring in the first year of the study delayed maize planting for several weeks allowing recovery of the groundcover after suppression. However, maize planted in zone-tilled bluegrass suppressed with paraquat yielded nearly as well as conventional maize. In the two subsequent years, several of the perennial groundcover treatments performed as well as conventional maize. They concluded that bluegrass suppressed with paraquat in the spring was the least competitive groundcover allowing grain production commensurate to conventionally grown maize. Perhaps the key finding of their work is that despite the benefits provided by groundcover in the spring, it behaves much like a weed in terms of maize establishment and requires suppression to enable the emergent maize crop to establish.

The intensity of tillage has an impact on crop yield as well as soil erosion and water infiltration. Zone tillage was superior to no-till management for maize grown with perennial groundcover [81]. In that study, the tilled zones where maize was planted were 25 cm wide and approximately 20–25 cm deep. Perennial groundcover was grown between each adjacent row of maize which was planted on 76 cm centers. It may be possible to further attenuate competition between maize and groundcover by altering the width of tilled zones and changing the geometry of their placement. Increasing the width of tilled zones to 51 cm would double the tilled soil over that used by Wiggans et al. [81] and should favorably alter the red:far red radiation sensed by the emerging maize plant perhaps reducing or eliminating the SAR. Alternatively, tilled zones could be further widened such that each row of maize is exposed to groundcover on only one side, which would also reduce red:far red ratio. Since many of the candidate groundcover species spread laterally by vegetative growth it should be feasible to migrate vegetative strips across a field over time so the entire upper soil volume receives the benefit of perennial cover for a fraction of time proportional to the base cover provided.

5.1.4. Enhancing Crop Competitiveness

Uniform maize emergence is critical for achieving high grain yields. The presence of groundcover intentionally alters the rhizosphere to promote soil health and biological activity. However, the groundcover may alter the soil environment in ways that are detrimental to germinating seed and developing seedlings. Under groundcover, soils remain colder longer, creating additional stress to the germinating seed and hindering crop stand establishment [113]. Uneven stand establishment ultimately has a negative impact on grain yield.

Seed is key to enhancing stand establishment and crop competitiveness under PGC. Seed must be genetically adapted to emerge under these stressful conditions but also must have exceptional quality. Seed viability and vigor (collectively known as seed quality) are a measure of the seed's metabolic efficiency. In maize, where a single seed produces a plant with a single ear (seldom two ears), the relationship among seed size, seed density, emergence uniformity, and seed yield is not clearly understood. Some reports assign little importance to maize seed size when seeds are planted under ideal conditions [113–115]. However, the stressful planting conditions of no-till agriculture [113] or cold soils and increasing planting depth [115] negatively affect seedling emergence. Seed quality and seed genetic potential are more important for uniform seed emergence than seed size [113]. Understanding interplant competition dynamics and plant-to-plant yield variation could provide new management tools for future yield gains in maize, especially when planted with a perennial groundcover.

The competition for water, light, and nutrients between an established PCG and seed has been studied in trees [116,117], mixed grass-broadleaf communities [118,119], and between weeds and crops [120,121]. PGC and crop root architecture [118,122] and light wavelength during early seedling development [81,86,123] can affect interplant competition and dry matter accumulation and yield. These studies, however, did not consider seed quality variability. Understanding the role of seed quality on interplant competition dynamics between maize seedlings and PGC, and between plant-to-plant competition and yield, could enhance crop competitiveness and provide new management tools for enhancing future yield gains in maize.

Management of weeds in PGC systems will differ from current systems in some respects, but will be similar in others. A number of herbicide modes of action currently are labeled for utilization on maize in the U.S. that do not kill perennial grass species [88,124]. Application equipment is available for strip application by shielded sprayers to protect susceptible crops and/or PGC [125] from herbicides with activity against either system component. The presence of PGC may influence crop-weed competitive interactions, weed population dynamics, and weed demographic processes. Besides providing a direct competition to weeds for space, light, moisture and nutrients, provision of PGC likely will contribute to annual losses in weed seed banks by enhancing invertebrate predation and microbial decay of weed seeds in the soil. PGC will act as a living mulch and aid in decreasing the red:far-red ratio of the light transmitted to the soil surface which can potentially inhibit weed seed germination and seedling growth, thereby reducing the early-season weed interference and yield losses in the maize crop [126–129]. The use of PGC systems in maize-soybean production may well promote resilient, ecologically based weed management strategies, and reduce herbicide inputs and their adverse impact on soil, water, or natural habitat [130,131]. Furthermore, the decreased reliance on herbicides will aid in preventing or delaying resistance evolution in weed species to multiple herbicide modes of action [131], which is currently a significant pest management challenge for growers (predicted annual losses of approximately US$ 43 billion in maize and soybean grown in the North America). Likewise, PGC may impact diversity and abundance of maize arthropod pests or predators and parasitoids of maize arthropod pests [132], but these areas not yet researched.

5.2. Plant Breeding and Genetics

5.2.1. Developing PGC Cultivars

Cool-season perennial grasses are collectively a group of grass species that are well adapted to the humid temperate region of the Midwest U.S. Many of them including Kentucky bluegrass, ryegrass (*Lolium perenne* L.), tall fescue, orchardgrass (*Dactylis glomerata* L.), bromegrasses (*Bromus* spp.), fine leaf fescues (*Festuca* spp.) and bentgrass (*Agrostis stolonifera* L.) are used for forage, turfgrass or soil conservation.

Cool-season perennial grasses are ideal groundcovers for annual grain crops because of their unique physiological, morphological and developmental characteristics that make them highly compatible with annual grain crops with minimal competition. Most cool-season grass species co-evolved with domesticated animals in the Eurasia region, developing culmless stems in which the growing point and the internodes remain close to the soil surface until inflorescence development is initiated, allowing these species to escape from grazing or mowing injuries [133]. The short plant stature of these cool-season grasses would result in less competition with the main crop for light and space. Cool-season grasses have a fibrous root system with extensive root hairs that cling to soil particles, making them ideal for soil erosion control. Branching in cool-season grasses occurs in the form of tillers, rhizomes or stolons with adventitious roots forming at nodes of the latter two, which can quickly fill in any empty space following harvest of grain crops providing desired ground coverage. The growth of rhizomes and stolons is reduced by severe shade from an actively growing maize or soybean canopy during the summer months, but it can quickly resume once they are exposed to full sun following crop harvest, resulting in a desirable "contraction-expansion-contraction" recurrent growth cycle of PGC that minimizes competition with the grain crop during summer and maximizes groundcover after grain harvest (Figure 7).

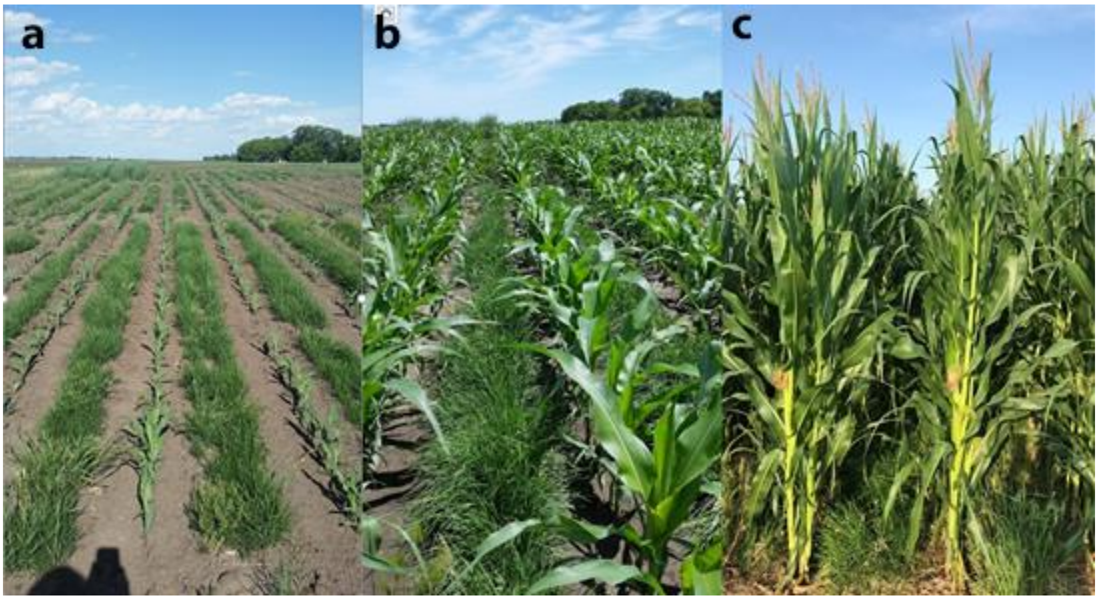

Figure 7. Maize production with Kentucky bluegrass as ground cover ((**a**) 31 May, (**b**) 13 June and (**c**) 10 July 2018). Kentucky bluegrass was established in the fall of 2017. A grass-free zone was created in the spring of 2018. Maize hybrid, DeKalb DB57-75RIB (refuge in bag) was planted at 32,000 seeds per acre on 30 April 2018. Maize grown with the Kentucky bluegrass cultivar 'Shannon' yielded at least 90% of the grain yield obtained from the non-PGC control plots without using any additional agronomic practices to control interspecific competition.

While cool-season grasses already possess many traits desired in PGC, no single species has them all. Therefore, developing improved, dedicated PGC cultivars with multiple desirable traits is critical. Current breeding efforts for cool-season grasses are directed towards developing better forage or turfgrass cultivars and no breeding program for developing cultivars dedicated to be used as PGC exists. Despite major differences in breeding objectives between forage grasses and turfgrasses, improved stand persistence with verdure is a primary breeding objective for both. Consequently, some traits desirable for PGC such as summer dormancy or shallow roots are often strongly selected against and as a result lost in many elite turfgrass and forage cultivars. It is therefore necessary to identify these traits in unimproved or wild accessions and integrate them into otherwise adapted cultivars as part of any PGC breeding program.

Great progress has been made in breeding forage and turfgrass despite its small research community [134]. Early 1940s marked the beginning of cultivar development for forage grasses with the release of a landmark tall fescue cultivar 'KY-31' in 1943 and another high impact tall fescue cultivar, 'Alta' in 1945 [135]. During the same decade, several Kentucky bluegrass cultivars were also released without extensive breeding and selection. These cultivars were generally referred to as common Kentucky bluegrass including South Dakota Certified, 'Park' and 'Troy', which generally have erect growth habit and rapid vertical growth rate. The Kentucky bluegrass cultivar, 'Merion' released in 1947 by the United States Golf Association, Green Section was the first true turf type cultivar with improved turf quality and much slower vertical growth rate [136,137]. Its release ushered in an era of active turf-type Kentucky bluegrass breeding that has resulted in hundreds of new cultivars. Since then, plant breeding efforts have been expanded to many other cool-season grass species. Given that cool-season grasses already possess many traits of the ideotype for an ideal PGC, we envision that future PGC breeding efforts will focus on improving the traits of summer dormancy, shallower roots and other desirable traits such as the ability to inhibit the nitrification process.

Entering dormancy early in the summer by PGC minimizes the competition for water and nutrients between PGC and the grain crop and minimizes SAR. Some *Poa* species including Kentucky bluegrass, Sandburg bluegrass (*Poa secunda* J. Presl) and bulbous bluegrass (*P. bulbosa* L.) enter dormancy during summer (Figure 8). Summer dormant forage type tall fescue cultivars have recently been developed [138]. It is well established that lack of soil moisture triggers summer dormancy in Kentucky bluegrass, whereas in Sandberg bluegrass the photoperiod is the likely trigger [136,139,140]. Summer dormancy triggered by a photoperiod or heat is preferred as they are more reliable environmental cues. We are currently evaluating the summer dormancy response of a number of USDA-GRIN Sandburg bluegrass accessions to identify accessions with early summer dormancy. Such accessions can either be further improved for direct use as PGC or be used for developing Kentucky bluegrass with improved summer dormancy through interspecific hybridization [141]. Similar screening for summer dormancy can be done for USDA-GRIN tall fescue accessions in order to improve tall fescue or related *Festuca* species with enhanced summer dormancy.

Utilizing PGC with yield-enhancing traits will likely lead to quick adoption of the PGC-based cropping system. Ishikawa et al. [142] showed that Koronivia grass [*Urochloa humidicola* (Rendle) Morrone & Zuloaga], a pasture grass widely grown in humid tropical areas greatly suppressed the nitrification process, a bacteria-driven process that leads to nitrogen loss from the soil, lowers crop nitrogen use efficiency and causes environmental degradation. A key chemical compound, brachialactone, a cyclic diterpene secreted from roots was shown to be responsible for this biological nitrification inhibition (BNI). In addition, the BNI trait has been shown to be genetically controlled [143], suggesting that development of cool-season grass cultivars with enhanced BNI is feasible. Interestingly, perennial ryegrass has already been shown to possess the ability to inhibit nitrification [144,145].

The majority of cool-season grasses are outcrossing, therefore abundant natural variations exist among populations or cultivars, providing an excellent opportunity to make genetic gains [146–149]. These variations have not been explored specifically for developing cultivars for use as PGC. The significant contribution of plant breeding has been abundantly demonstrated for major crops and we expect the same can be accomplished if dedicated breeding programs for developing PGC are established.

Significant progress made in genome sequencing, molecular biology and biotechnology [150,151] will undoubtedly empower plant breeders to develop superior PGC cultivars.

Figure 8. Summer dormancy as shown in browned Kentucky bluegrass following an extended period of extreme drought (**a**) and in Sandburg bluegrass grown with maize (**b**).

5.2.2. Developing Maize Hybrids Adapted to PGC Systems

Maize genetics and generally plant breeding is gradually transitioning from a black box approach, largely agnostic of genes and alleles affecting trait variation, to a discipline, where decisions where decisions are based on (1) a deep understanding of which combinations of genes and respective alleles lead to improved breeding populations and cultivars and (2) massive testing of selected candidates. Currently, genomic selection is an extension of traditional breeding methods, where large numbers of genotypes are evaluated first at DNA and a selected fraction at the more expensive agronomic levels, to ultimately identify a limited number of superior experimental variety candidates. With a more complete understanding of which gene and respective allele combinations would result in the optimal genotype for a given environment, more targeted approaches are expected to emerge, which will enable their design. The question is no longer, whether a tool or approach is available, but which of the increasing number of options should be chosen, given limited financial resources, to maximize both genetic gain and economic return.

The rate of genetic gain for grain maize [152] during 1930–1960s was 55.5 kg/ha/year, which rose to 99.3 kg/ha/year in subsequent decades. Maize has a rich pool of genetic diversity to help breeders create improved germplasm. It is the most widely grown agricultural crop in the world and a pre-eminent experimental model plant. Substantial resources have been established, including the first maize genome sequence from inbred B73 [153], followed by an increasing number of sequenced genotypes [151,154–157]. At this rate, dozens, if not hundreds, of sequenced maize genomes will be available in the near future.

Discoveries of genome organization, maize diversity, precision envirotyping [158], genomic selection [159,160], genome editing [161,162], and speed breeding [163] coupled with eco-physiological crop models [164] have potential to modify or completely redesign maize genetic improvement models. If maize hybrids specifically adapted to PGC systems are needed, then modern breeding approaches will enable their development within a short time period.

Maize cultivars grown in perennial groundcover face different challenges with regard to exploiting their yield potential compared to current "clean" weed-free production conditions. During the first weeks of cultivation, maize is sensitive to shifts in red to far-red radiation. Groundcover may elicit SAR with an associated negative impact on grain yield. Groundcover also affects the microclimate for emerging maize seedlings by reducing temperature and increasing moisture compared to conventional growing conditions. Thus, maize genotypes adapted to perennial groundcover cultivation need to be less sensitive to red:far red radiation to avoid SAR, and possess better abiotic stress tolerance to thrive when grown with groundcover. It is conceivable, but untested yet, that different maize genotypes are optimal under perennial groundcover versus conventional cultivation conditions. However, while establishing and running a dedicated breeding program for maize cultivars in PGC would be possible, it would be very costly. It will thus be important to determine in field experiments, whether there are Genotype x Management interactions, or whether the same genotypes performing well under conventional cultivation conditions are generally superior under PGC conditions. The same question applies to soybean and other crop species.

5.3. Soil Health and Nutrient Management

More than half of the organic C that was present in the native prairie soils of the U.S. Midwest has been lost as a consequence of row crop agricultural systems. Although records of soil organic carbon (SOC) levels in Midwest prairie soils prior to European settlement are lacking, evidence for supporting this enormous loss of soil organic C due to cultivation comes from studies of long-term plot trials [21] and 'across-the-fence' comparisons of soil organic C levels in long-term cultivated fields with adjacent 'never-been-plowed' prairie remnants (Table 1).

Table 1. Comparison of soil organic C levels (0–15 cm) in adjacent native prairie remnants and long-term cultivated fields in Iowa. Paired soils sampling sites were selected within 20 m of each other and within the same soil map unit. Soils were sampled an analyzed using methods described in Russell et al. [165].

Site	**Prairie**	**Cropped**
	(kg-C/ha)	
Hayden	182,290	126,311
Chipera	169,809	68,170
Larson	146,590	81599
Kalsow	143,086	94,879
Doolittle	106,766	71,665
Ketelsen	98,362	47,726
Average	**141,151**	**81,725**

The lower level of soil organic C in cultivated soils, relative to soils under native prairie vegetation, is due in part to greater erosion of organic matter rich top soil in the cultivated fields, in part to accelerated oxidation of labile soil organic matter because of enhanced soil aeration caused by tillage, and in part to decreased C inputs in row crop soils relative to native prairie soils [18,166]. In native prairie soils, a dense and integrated root-mycorrhizal network literally permeates every cubic millimeter of the top soil and can extend with decreasing density to depths of up to 2 m [167]. This root-mycorrhizal network is present year round and is continuously turning over as old roots and fungal hyphae die and new roots and hyphae grow to replace them [168]. This turnover means that native prairie soils receive a continuous and large input of root and fungal biomass C, which through the process of humification is transformed into new soil organic matter [169]. Cultivated soils by contrast receive a much smaller annual input of root and fungal biomass and the integrated root-mycorrhizal network is present in cultivated soils for only about 3 months of every year. Thus in cultivated fields, soil organic C is being lost through microbial respiration without any input of new biomass C for 9 months of every year.

The integrated root-mycorrhizal network under cool season perennial grasses extends only through the topsoil; hence the benefits of cool season grasses for soil quality are largely confined to the topsoil. The topsoil, however, is critical for building soil organic matter and maintaining soil quality, hence cool season grasses provide many of the same benefits as native prairie. The presence of any actively growing surface cover, whether deep or shallow rooted, greatly increases surface water retention and infiltration relative to a bare soil surface. In cultivated fields, rain falling on bare soil will form a crust on the surface of the soil which inhibits infiltration and increases surface runoff, even when a crop canopy is present. Hence, without a surface mulch, tilled soils are highly vulnerable to erosion. The presence of crop residue mulch, as found in no-tillage systems, reduces the formation of surface crusts and enhances surface water retention and infiltration, but cannot provide the belowground benefits of a living mulch. New soil organic matter is predominantly formed from root and fungal hyphae biomass C as much of the C in surface residues is mineralized and released as CO_2. For example, Gale et al. [170] reported that 75% of new soil organic C came from root biomass and only 25% came from surface residue in a simulated no-till oat (*Avena sativa* L. cv. Ogle) cropping system.

Long-term field plot studies have demonstrated that cool-season grasses are effective for improving surface soil health relative to various cropping systems. For example, Laird and Chang [35], compared ten soil quality indicators from a long-term (19 years) field plot study that included a bluegrass control along with no-tillage, chisel plow tillage, and moldboard plow tillage and with and without residue removal treatments. Surface soil (0–5 cm) under the bluegrass sod had 1.29, 1.26, and 1.11 times higher total C, total N, and CEC values, respectively, than surface soils under no-till cultivation. However, surface soil under the bluegrass sod had 2.45 and 2.01 times larger nitrogen mineralization potential and basal respiration rate, respectively, than soil under no-tillage. These results indicate that crop residues left on the surface in no-till systems are not as effective as a living mulch in building levels of labile soil organic matter and in promoting healthy biologically active soils.

5.4. Ecosystem Services and the Environment

Many of the ecosystem services of the tallgrass prairie were lost as a consequence of the conversion to annual crop production [171,172]. Services included soil health; clean water; regulation of climate, erosion, and pests; flood control; and wildlife habitat. Farmers, policy makers, and society at large increasingly recognize that agroecosystems benefit from conservation practices that restore these services. However, these important services that are socially valuable may not be immediately obvious or easily quantified [173–175]. Choosing a sequence of crops and the practices used for growing them represents a complex set of economic, ecological and social decisions that will determine what ecological services are delivered by agricultural lands. An ecosystem services framework (ESF) that links the functioning of an agroecosystem to human welfare has been useful in evaluating cropping systems to identify trade-offs and opportunities for 'win-win' scenarios [176]. For example, Schipanski et al. [177] used an ESF to evaluate the introduction of cover crops into 3-year maize-soybean-wheat rotations and found that cover crops increased 8 of 11 ecosystem services. The full valuation of ecosystem services provided by a cropping system is only possible after the system is fully developed and implemented at scale. The development of economically and agronomically viable PGC systems compatible with maize and soybean production is still in an early stage of development. However, studies of the ecosystem consequences of partial perennialization of the maize-soybean production system are available and these provide a reasonable basis from which to make informed predictions about the likely performance of PGC systems.

The impact of a PGC system on the provision of ecosystem services will depend on a wide range of PGC characteristics such as root depth and growth rate, as well as local conditions such as soil characteristics and slope, and also on both local climate and weather. A successful PGC system should function in some important ways like vegetated buffers and cover crops. The extensive study of these conservation measures give a hint of what we can expect from a well-designed PGC.

Hydraulic regulation and water purification services provided by vegetated buffers, filter strips, and cover crops have been examined for many crops, locations and years. Mayer et al. [178] performed a meta-analysis of nitrogen removal in buffers and found that that buffers of various types were effective at removing nitrogen, that wider buffers were more effective at removing nitrogen and that nitrogen removal was not related to flow pattern or vegetation type. This agrees with a subsequent meta-analysis of vegetated buffers by Zhang et al. [179] that quantified the relationships between pollutant removal efficacy and buffer width, slope, soil type and vegetation type. The most important predictive factor of pollutant removal efficacy was buffer width. Removal efficacy was found to increase nonlinearly with buffer width, and buffer width alone explained large percentages of the variance in removal efficiency for sediment, pesticides, nitrogen and phosphorous. A PGC system can be thought of as series of vegetative buffers located across the field surface. Sediment, nutrient and pesticide removal efficiency will vary with local conditions, particularly the depth and nature of drainage flow, however, a PGC is likely to provide very high removal rates.

Vegetative filter strips are a conservation practice commonly used throughout the U.S. Corn Belt to control runoff and the transport of sediment. Filter strips are typically 5 to 15 m-wide strips usually along the bottom of a sloped field and often planted in tall fescue or other short cool-season grass. Filter strips effectively reduce runoff (both inter-rill and concentrated flow) as well as sediment transport [180,181]. A PGC system that is well-established and is contour planted can be expected to effectively function as a series of vegetative filter strips that cover the entire field surface except the planting rows. Such a system should dramatically reduce overland flow and sediment transport compared to a typical maize field with bare soil under the crop.

Biological control services are the regulation of crop pests and diseases. These services are the product of complicated ecosystem processes that vary over time and across the landscape. Although the impact of PGC on biological control is uncertain and is likely to be highly variable, there are reasons to be optimistic. In some agricultural settings, growing a perennial cover beneath the main crop is common practice [182]. For example, perennial cover crops are the norm in apple (*Malus sylvestris* L.) production. The cover is permanent between rows with bare soil along the tree row. The services provided by the perennial cover include weed suppression and improved nitrate management [183]. Living mulches are also successfully grown concurrently with several vegetable crops and support the hypothesis that cover crops can reduce some pest populations [184,185]. A review by Bianchi et al. [186] found enhanced natural enemy activity associated with herbaceous field margins. Prasifka et al. [187] found that living mulches grown with a maize-soybean rotation increased predator abundance and consumption of European corn borer (*Ostrinia nubilalis* Hübner). What evidence there is suggests that there are opportunities for improved pest management with PGC, but there is also evidence that some perennial cover can worsen pest problems. For example, soybean aphid is known to use various buckthorn (*Rhamnus*) species as a primary host in early spring before the availability of soybean plants [188]. Much more needs to be learned about the effect of PGC on crop pests, their natural enemies and crop diseases, but it is clear that when designed correctly, perennial groundcovers can provide valuable biological control services.

The use of a PGC in maize production is expected to increase the sustainable provision of biofuel feedstock while maintaining grain production. Several studies have observed that synergies between annual cover crops and maize stover removal can increase sustainable stover removal and farm profits [189]. The capacity of the PGC to reduce erosion, maintain or increase soil organic carbon, and retain nutrients is likely to be equal to or larger than that of an annual cover crop and allow maize stover to be harvested sustainably at rates much higher than possible with current management practices. Bonner et al. [190] performed a detailed model-based estimate of sustainable maize stover harvest in five U.S. Corn Belt states (Nebraska, Iowa, Illinois, Indiana and Minnesota). Stover harvest was constrained to not exceed tolerable soil loss rates (T values) and maintain a soil conditioning index (SCI) > 0. The addition of a winter rye cover crop to a baseline of current conservation tillage practices increased sustainable stover harvest by 51% over the baseline. The use of the cover crop and a 3 m wide, single native perennial grass barrier located in the middle of the slope profile increased sustainable stover harvest by 75% compared to the baseline. The imposition of more severe sustainability constraints (total erosion < 1/2 T, SCI > 0, and SCI-OM > 0) increased the importance of these conservation measures. Under these constraints, use of the cover crop and vegetative barriers increased the potentially available maize stover within the five states by 207% relative to the baseline management scenario. Based on the results of the analysis of Bonner et al. [190], it seems reasonable to expect that a well-designed PGC system would allow a substantial increase in sustainable stover harvest.

Although the ecosystem service impacts of PGC are highly uncertain, there is sufficient scientific study of related systems such as living mulches, cover crops, and filter strips to suggest that a well-designed PGC system is likely to lead to greater ecosystem services. It will be important to quantify the direct economic impacts of PGC as well as the less tangible value of ecosystem services. The major challenge facing the dominant maize-soybean production system today is the loss of ecosystem services that have direct societal consequences such as declining water quality, increased flooding, and expanding hypoxic zones, but also the loss of soil fertility that is required for continued agricultural productivity. The PGC system is a promising approach to expanding the ecosystem services provided by the agricultural landscape of the U.S. Corn Belt while also preserving farm profitability.

5.5. Economic and Sociological Factors

Producer adoption of a PGC system requires agronomic feasibility and evidence of positive agro-environmental impacts, but ultimately scientists must be able to quantify and communicate its economic feasibility to invoke adoption. Current maize and soybean rotations in the Midwest have path dependency owing to long-standing and familiar agricultural and conservation policies, the significant capital investments of farmers and retailers in the supply chain, commodity market and pricing structures, and organized political forces. Large-scale adoption of alternative cropping systems must meet these imbedded technologies, institutions and market advantages head-on, and it is likely that shifting to a more regenerative system such as the proposed PGC in the Midwest faces a long-tailed adoption path.

5.5.1. Socio-Economic Feasibility: Benefits and Costs

A PGC system adapted uniquely for Midwest agriculture has the propensity to generate pecuniary benefits that imply improved farm revenue from crop yield improvements and greater maize stover extraction. Modern high-yielding maize hybrids produce large quantities of stover that may interfere with the following maize crop, an autotoxicity mechanism known as "yield drag" [191]. A regenerative system with optimized maize hybrids could allow producers to remove and market more of the maize stover and generate positive yield impacts on the following crop. There is evidence that biochar, a byproduct of certain stover processing systems, when applied to fields, can also mitigate the potential negative effects of maize stover removal and also reduce nitrogen leaching from soils [192].

Pratt et al. [189] found that benefits from groundcover varied widely (from US$ 75/hectare to US$ 192/hectare) depending on the assumptions about the amount of added nitrogen obtained from the cover crop. Higher net returns may also be achieved through lower input costs because of increased future productivity, reductions in soil erosion, moisture retention, and reduction in fertilizer loss from leaching (which lead to lower applications of fertilizer, pesticide and herbicide). These benefits are harder to measure and no market price for them exists, making incorporating them in standard cost-return analyses and explaining them to producers difficult. Finally, adoption of new, regenerative production technologies may convey positive rural community impacts, with the potential to not only stabilize the profitability of the farming system, but additionally to stimulate local economies and generate new enterprises to support the PGC system and opportunities for employees and firms in in the associated value chains.

Quantifiable costs include the price of groundcover seeds, expenditures related to planting, the management and maintenance of the groundcover crop (herbicide and fertilizer application when needed, chemical suppression, etc.) as well as capital investment in the form of new machinery and/or modifications of existing machinery to accommodate the new cropping system. The additional management responsibilities associated with adoption of perennial groundcover, which include the mitigation of competition between groundcover and the primary crop, are part of the non-quantifiable costs. Even more difficult to measure are the impacts on timing of operations, changes in farm benefits (for example, crop insurance), soil health, changes in water quality, and the perceptions and beliefs of farmers about the benefits of adopting groundcover.

Quantifying economic benefits and costs is crucial in determining a system's profitability and break-even prices and yields. In addition to measurable benefits and costs, there are non-quantifiable gains and opportunity costs associated with the proposed PGC system, which makes it difficult for farmers to determine expected net returns and make informed decisions about adoption. As the PGC system is developed and optimized, research focused on quantifying producers' choices within a system (e.g., hybrid selection, rotation options, and biomass removal based on production characteristics) and developing realistic pecuniary costs and benefits, even for those factors that are yet un-priced, that identifies a profitable system with a favorable risk profile is the most effective pathway towards voluntary producer adoption.

5.5.2. Lessons Learned from Cover Crops and Other Conservation Practices

Producers using traditional maize-soybean rotation systems in the Midwest U.S. have a number of federal, state and regional working-land programs and alternative production practices available to mitigate the established negative soil and water impacts: Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP), Conservation Reserve Enhancement Program (CREP), Resource Enhancement and Protection (REAP in Iowa), cover crops, low- and no-till production, and so forth. Yet to date, the use of established conservation practices in the highly-productive agricultural Midwest region is relatively low. A 2017 Iowa Farmland Ownership and Tenure Survey [193] shows that approximately 8% of Iowa farmland was in some type of state or federal conservation program, 27% of Iowa farmland was no-till, 4% had cover crops, and 3% was in buffer strips. The voluntary use or adoption of any of these often comes down to expected returns: will the practice or program enrollment provide an equal or greater return to the land and/or does it reduce the variance in returns over time? A producer may be reluctant to enroll portions of a field into a state conservation program because it requires a longer-term commitment. Returns to commodity production may be higher in the future, and locking into conversation practices vis-à-vis federal or state programs, that are costly to install or reverse creates risk, and therefore an adoption barrier.

Producers evaluate the profitability and economic feasibility of their production systems. Given the current state of knowledge, a PGC system introduces new risks, and producers make tradeoffs between the benefits, costs and risks associated with implementation of a different cropping system [177], such as cover crops. Depending on the type of cover crop and management regime used, changes in crop management imposes differential production costs [194], and varying impacts on crop yields and therefore profitability bring about uncertainty in expected net returns. Lu et al. [195] highlight the variability in the profitability of cover crops in grain production based on the type of cover crop. According to Pratt et al. [189], agronomic benefits of groundcover can range from a net loss of US$ 11.09/hectare to a net gain of US$ 87.32/hectare. Given that the presence of cover crops may increase or decrease yields, the impact on productivity is uncertain. The same applies to fertilizer and herbicide application, which could decrease because of reduced loss through leaching or increase due to application on cover crops (see Section 5.1.4), and groundcover persistence and competition with the primary crops. Furthermore, timing of field operations is important so as not to interfere with cash crop responsibilities and production [194,196]. A PGC system may be shown to decrease the production costs and create an opportunity for an improved economic profile; however, it introduces production complexities and new uncertainties into the decisions that will influence producers' willingness to adopt them [197,198].

5.5.3. Policies and Mechanisms to Incent Adoption

The adoption of the PGC system has policy implications and will likely require market-based incentives to promote larger-scale adoption early in the system's life. Federal and state programs to promote conservation practices are already in place, but farmer education and policy support to encourage adoption of cover crops until sustained expected revenues are realized may be key to the adoption of a PGC system by farmers. Bergtold et al. [194] outline the changes in the Federal Crop Insurance Program, which allows for the use of groundcover by farmers without affecting their crop insurance eligibility (which was not the case in the past). However, farmers must abide by the Natural Resources Conservation Service (NRCS) guidelines regarding cover crop termination to ensure eligibility. Zhang et al. [193] report that farmers are more likely to adopt conservation practices, which include cover crops and no- or low-till systems, when there are policies in place to get cost-sharing and tax credits for doing so. An extensive study regarding farmers' private returns to cover crops shows that though private net returns are negative, even with cost-sharing, the ability to graze livestock on the cover-cropped acres in the spring or harvest it for biomass yields positive net returns [199]. Traditional conservation programs limit grazing of livestock or harvesting biomass when cost-share conservation practices are used; this is policy that may need adjusting to incentivize a PGC system.

6. Conclusions

Perennial groundcovers offer the potential for addressing environmental concerns associated with soil and water degradation while also increasing crop productivity and profitability (Figure 9). A perennial groundcover need not have any direct economic value. Its worth comes from adding value to the associated grain crop by allowing a greater amount of stover to be sustainably harvested and improvements in subsequent grain crop performance. The provenance of enhanced ecosystem services, also has economic value, but currently there are no universally accepted mechanisms for assessing these at the farm level. The emerging markets for advanced biofuels will create demand and value for harvested stover. Producers will be able to simultaneously harvest a food and energy crop from the same land without causing undue environmental damage. In order to meet the projected biomass demand, alternative cropping systems that reduce the vulnerability of land to environmental degradation must be developed and implemented [33]. Maize production systems that use perennial groundcovers would allow removal of crop residue with minimal negative effects on soil and water quality [34].

A remarkable aspect of the productivity of perennial groundcover systems is that it has been achieved using technologies and germplasm developed for conventional production practices. It is easy to imagine more advanced systems that use groundcover varieties, maize hybrids, and soybean varieties that are specifically adapted to perennial groundcover systems. Groundcovers could be developed through conventional and molecular breeding systems that possess the traits described above. Maize hybrids could be identified that are less sensitive to early-season competition and tolerate potential interferences from ground covers. Additionally, machinery could be designed to better manage crops growing in association with perennial groundcovers. Part of the success story of modern crop production is the ability to precisely plant crops. Planters could be designed that accurately plant maize into strips to minimize proximity to the cover and using sensors detect when the cover needs restoration and reseeding as necessary. Tillage, fertilization, and suppressant application could be combined to reduce the number of passes of field machinery required. This would save time and also reduce the negative effects of soil compaction caused by repeated field traffic.

The idea of producing grain and oilseed crops with a perennial groundcover is not as radical of an idea as it first appears. Less than a century ago farmers were growing open-pollinated varieties of maize which were planted at very low populations. Thus the genetics and the management practices were different. Architecture of the mature maize canopy was very different than today and grain yields were also much lower; 10–20% of what they are today. Weed management was achieved by cultivation as there were no herbicides. Contrast that to today, where the crop is planted with laser precision at very high populations with seed treated with chemicals to inhibit pests. Modern hybrids are modified genetically to resist insects and diseases and to tolerate herbicides directed at weeds. Fields are scouted and pests controlled using integrated strategies involving cultural, biological and chemical controls. To the extent possible, every variable affecting production is controlled so that an environment favorable to crop production is achieved.

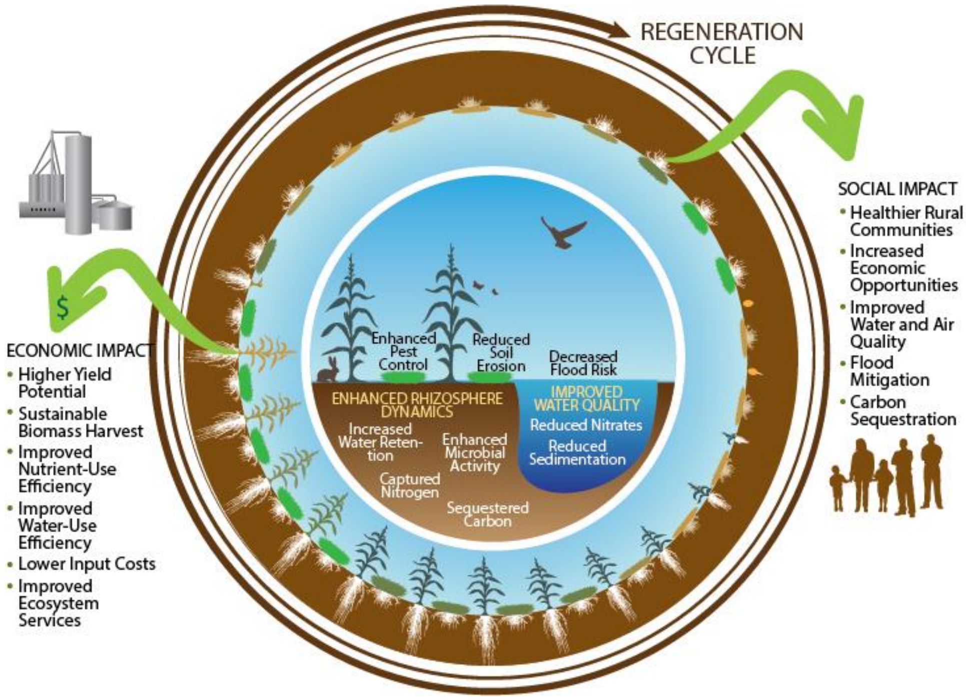

Figure 9. Illustration of interplay between perennial cover and annual crop over a growing year for the proposed system (mid-winter is up). Key events are illustrated clockwise from top, including spring planting of primary crop coinciding with induced die-back of perennial crop, early growth of primary crop while perennial is dormant, resurgence of groundcover as primary crop matures, and continued presence of groundcover post-harvest. Each complete cycle further regenerates soil health and ecosystem stability. The economic and social impacts represent goals to be achieved and have yet to be verified by research.

The proposed changes in the production system are modest by comparison especially given the magnitude of potential benefits to the environment. By including a perennial plant in the system, functional traits inherent in the native flora can be fostered with attendant environmental benefits. To accommodate the perennial species, tillage practices will need to be altered to some extent. Either no-till or more likely strip-till methods will be required. Using the latter method, farmers will still be able to prepare an ideal seedbed for planting, incorporate nutrients and amendments and perhaps mange the soil in new ways that build rather than deplete organic matter with its associated benefits to soil quality.

At least for the near term, the groundcover will need to be suppressed in the spring when it behaves much like a weed with respect to the developing maize seedling. Farmers are already altering weed management strategies as weeds resistant to glyphosate are becoming common [200]. They are returning to pre-emergent and other early-season control strategies. Applying a chemical suppressant either concomitant with tillage or planting is probably not a serious challenge, although the consequences of not doing so are arguably much greater in a PGC system. Development of new groundcover varieties, maize hybrids, and soybean varieties will lessen the risk associated with early-season competition from the groundcover and reduce the severity of treatment required to suppress the groundcover.

It is unreasonable to expect the adoption of perennial groundcover production systems until they have been more thoroughly studied and have been developed to be as robust as conventional systems. The potential to improve the environment and long-term sustainability of maize production more than justifies the investment in genetics, machinery, and other inputs necessary for managing PGC systems. The potential is real, but it will take substantial development by all components of the agricultural industry to achieve it.

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