Restoring social and ecological relationships in the agroecosystems of Canada’s prairie region

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Abstract

Ecosystem restoration is proposed as one aspect of the transformative changes required to meet global sustainability goals. In the prairie region of Canada, where the widespread and relatively recent conversion of natural ecosystems to farmland displaced Indigenous peoples and made way for a thriving agricultural sector, I propose that ecosystem restoration requires two intertwined transition processes: reorienting worldviews to embrace the social and biophysical contexts of local ecosystems, and taking practical steps to restore ecosystem functioning and integrity. Attention to ecosystem functioning—the relational processes that undergird the desired outcomes—can promote the design and implementation of agricultural landscapes that mimic key features of natural ecosystems while maintaining a mix of land uses. Human ingenuity and thoughtful integration of traditional and scientific knowledge are needed to develop locally adapted land use that supports synergetic relationships within and among farm fields and other landscape features. Integrating social goals into the design of agricultural landscapes can spawn creative solutions but will require a shift toward a more open and collaborative approach, especially regarding the use of privately owned lands.

Keywords

Ecosystem restoration, Canadian prairies, biomimicry, nature-based solutions, ecosystem functioning, ecological intensification, socio-ecological systems, farm system design

Introduction

Humanity’s well-being and very existence depend unequivocally on our relationship to the ecosystems that sustain us. Recent reports of human impact on Earth warn that we have likely already surpassed certain planetary boundaries associated with climate change, biodiversity loss, land use change, and biogeochemical flows (Newbold et al., 2016; Ripple et al., 2021; Steffen et al., 2015). Scientists and activists alike are calling for rapid, transformative change in how we relate to Earth, particularly in how we obtain resources to meet our physical needs (Ripple et al., 2021; Suzuki and Hanington, 2021).

Global attention has begun to look through the lens of ecological processes to help address these challenges, recognizing ecosystem services beyond obtaining economic products (Millennium Ecosystem Assessment, 2005) and pursuing nature-based solutions (Nesshöver et al., 2017). In an effort to reach global sustainability targets such as the Paris Agreement and the Sustainable Development Goals, the United Nations has declared 2021–2030 the Decade on Ecosystem Restoration, aiming to “prevent, halt and reverse the degradation of all kinds of ecosystems, contributing to reductions in global poverty and ensuring that no one is left behind” (United Nations Environment Programme, 2021: 6). This initiative includes restoration of farmlands, urban areas, and all types of terrestrial and aquatic natural ecosystems.

In the prairie ecozone of Canada, planetary boundaries and the need for sustainable development may seem distant or irrelevant. With its extensive and still-productive land base, the prairie region is a major producer of agricultural products, with an increasing share destined for export markets (Kissinger and Rees, 2009). Yet, this region is one of the most altered biomes in the nation and on the planet (Kraus and Hebb, 2020; Newbold et al., 2016). Conversion to farmland has caused the loss of >99% of tall-grass prairie, >70% of mixed-grass prairie, and 40–70% of wetland habitats (Federal, Provincial and Territorial Governments of Canada, 2010) and continues to threaten biodiversity in much of the prairie region (Kraus and Hebb, 2020). By rapidly adopting new technologies and seeking economies of scale, many prairie farmers now...
manage large tracts of land, leading to changes in the structure of the landscape as well as rural depopulation (Qualman et al., 2020). While highly successful in terms of agricultural productivity, converting prairie ecosystems to farmland has caused loss of soil organic matter and has altered local and regional water and nutrient cycles (Bartzen et al., 2010; Blann et al., 2009; VandenBygaart et al., 2003). Today, declines in indicators of ecosystem health, such as soil quality (Pennock et al., 1994), water quality (Blann et al., 2009; Malaj et al., 2020), and populations of grassland birds (Stanton et al., 2018), can be attributed to tillage, drainage, and application of fertilizers and pesticides—agricultural practices intended to maintain and increase crop productivity, sometimes under the banner of

| Research Question                                                                 | C | L | S |
|----------------------------------------------------------------------------------|---|---|---|
| **Prairie farm landscapes**                                                       |   |   | ✓ |
| Which biomimicry principles(*) merit more attention in our efforts to restore ecosystem functioning in agricultural landscapes? | ✓ | ✓ | ✓ |
| Which natural ecological processes tend to be most altered by farming, and how has this undermined desired ecosystem functions? | ✓ | ✓ | ✓ |
| Which landscape-scale processes tend to be ubiquitous among agroecosystems; which ones are sensitive to the local setting? | ✓ | ✓ | ✓ |
| How do natural and artificial landscape features interact to affect ecosystem functioning, and how can artificial structures be designed to mimic natural landscapes? | ✓ | ✓ | ✓ |
| What is the capacity of the agricultural landscape to absorb continual or periodic stresses imposed by agricultural production? | ✓ | ✓ | ✓ |
| Which landscape features or ecosystem processes are most vulnerable to human-induced stresses, and how can these weak points be bolstered? | ✓ | ✓ | ✓ |
| What proportion of agricultural land should be reverted to "natural" conditions, and how should the latter be arranged? | ✓ | ✓ | ✓ |
| What size, shape and arrangement of crop fields best maintain ecosystem functioning in a particular landscape? | ✓ | ✓ | ✓ |
| How can ecological succession (from annual to herbaceous perennial to woody perennial vegetation) be used to promote resilience of prairie farmlands? | ✓ | ✓ | ✓ |
| How can digital tools and agricultural technology (e.g., robotics, guidance systems) contribute to ecosystem functioning in a heterogeneous farm landscape? | ✓ | ✓ | ✓ |
| How can traditional and experiential knowledge best be interwoven with scientific approaches to understand evolving interactions in agricultural landscapes? | ✓ | ✓ | ✓ |
| **Crop production practices**                                                     |   |   | ✓ |
| Which ecosystem functions and processes can be mimicked readily within crop fields through beneficial practices? To what degree? Through which practices? | ✓ | ✓ | ✓ |
| To what extent can innovative combinations of annual crops in space and time mimic the ecosystem functioning arising in diverse perennial native prairie habitats? | ✓ | ✓ | ✓ |
| What features of native plants can be enhanced in crop plants to improve ecosystem functioning? | ✓ | ✓ | ✓ |
| How can we strategically accelerate ecological processes such as nutrient cycling or decomposition in cropland, without creating undue risk of losses? | ✓ | ✓ | ✓ |
| To what extent can farm systems self-organize, yielding mechanisms that support ecosystem functioning, and how would this affect the farmer’s role? | ✓ | ✓ | ✓ |
| **Native habitats of the prairie region**                                         |   |   | ✓ |
| Are native prairie habitats an appropriate benchmark for agricultural systems?    | ✓ | ✓ | ✓ |
| What features of natural ecosystems contribute most to ecosystem functioning and desired outcomes, and how universal are these relationships? | ✓ | ✓ | ✓ |
| How does spatial distribution of native habitats within prairie farm landscapes affect their functioning? | ✓ | ✓ | ✓ |
| How do external factors, such as climate change or nutrient deposition, affect the functioning of native prairie habitats, now and in the future? | ✓ | ✓ | ✓ |
| How do flows of nutrients, energy, water, and organisms between native habitat remnants and farmland affect their functioning? | ✓ | ✓ | ✓ |
| Which features of natural ecosystems can be enhanced by human management, and how? | ✓ | ✓ | ✓ |
| **Social dynamics**                                                               |   |   | ✓ |
| How does the “sense of place” differ among Indigenous/settler, rural/urban, or other demographic groups, and how does this affect farming practices? | ✓ | ✓ | ✓ |
| What constitutes a “good farmer,” according to farmers and non-farmers, and why do these perspectives differ? | ✓ | ✓ | ✓ |
| What barriers hamper adoption of environmentally beneficial practices on prairie farms, and how can they be allayed? | ✓ | ✓ | ✓ |
| What aspects of farm landscape design are amenable to multi-farmer collaborations, and how can such collaborative practices at landscape or regional scales be encouraged? | ✓ | ✓ | ✓ |

Additional columns indicate the direct relevance of research questions to cropland (C), other landscape features (L), and social aspects (S) beyond normal farm management practices.

Biomimicry principles: 1) runs on sunlight; 2) uses only the energy it needs; 3) fits form to function; 4) recycles everything; 5) rewards cooperation; 6) banks on diversity; 7) demands local expertise; 8) curbs excesses from within; 9) taps the power of limits (Benyus, 2002).
sustainability. The UNEP (2021) cites the historical conversion of western Canadian grasslands to farmland under the practice of summer fallow as a key example of the degradation of global grasslands, shrublands, and savannahs. While improvements in prairie farming practices have helped to stabilize loss of topsoil and soil organic matter, the fact remains that much of the prairie region now bears little resemblance to the ecosystems that dominated these lands before European settlement.

What is an appropriate approach to ecosystem restoration in this degraded but still-productive agricultural region? Complete restoration of all agricultural lands to native habitats is not a realistic goal, given current human needs for food. Neither, however, is continued loss of biodiversity and ecosystem functioning, given future human needs for a livable planet. I propose that ecosystem restoration can be achieved by thoughtfully designing agricultural landscapes that mimic the functioning of local natural ecosystems while maintaining a mix of land uses, ranging from intact natural habitats to annual cropping systems, and using both preventative and restorative practices. Developing this approach requires an accompanying worldview reorientation that sees humans as part of the land and strengthens social relationships, with careful consideration of the historical context. These interwoven approaches emphasize not only the outcomes required from an agroecosystem but also the ways they can be achieved.

**What is ecosystem restoration?**

According to the UNEP (2021: 7), “[e]cosystem restoration is the process of halting and reversing degradation, resulting in improved ecosystem services and recovered biodiversity.” This definition raises important questions: What do we mean by an ecosystem? Improved or recovered to what state?

An ecosystem can be defined as the “dynamic assemblage of soil, air, water, and all biota (including humans) in their interwoven interactions in a designated place” (Janzen et al., 2021: 2). Key aspects of this definition are the multiple, ever-changing interactions among components that engender ecosystem integrity (Anghinoni and Vezzani, 2021; Cabell and Oelofse, 2012; Tittonell, 2014), the unique local manifestation of these interactions, and the inclusion of humans. Many so-called natural ecosystems around the world, including those in the grassland and parkland regions of western Canada, were historically managed by humans, though with a considerably lighter touch than today. Relationships with other entities in our shared ecosystems are shaped not only by biological needs for food, water, shelter, waste management, a stable climate, and so on, but also by social factors such as concepts of human rights, tradition, prosperity, ownership, and power. Thus, ecosystems—both natural and managed—are based on a complex set of ecological and social relationships.

In general, targets for ecosystem restoration can range from reducing human impacts and improving ecosystem management to complete recovery of native ecosystems (Gann et al., 2019), though the latter target is not always attainable or desirable. While the nature of individual components and the ecosystem services produced are certainly an integral part of this approach, equally important are the relational processes that characterize the “functioning” of an ecosystem—the emergent properties that arise in a self-organizing system, contributing to synergies among components and resilience to stresses and shocks (Anghinoni and Vezzani, 2021). The ecological processes that promote ecosystem functioning include nutrient and energy cycling, hydrological flows, competitive and cooperative relationships within the biotic community, and successional dynamics and disturbances, among others. Key social aspects of sustainable systems include respect for diverse worldviews and knowledge systems, shared values among members of society, and equitable access to resources. The principles of biomimicry (See Table 1 footnote) similarly emphasize the processes and relationships involved in achieving the desired outcomes, while also guiding what those outcomes ought to be (Benyus, 2002; Mathews, 2011).

The path to ecosystem restoration in the Canadian prairies, I propose, lies in designing land use that restores and protects ecosystem integrity by enhancing the complex ecological and social relationships among its inhabitants, both human and non-human. This approach goes beyond the concept of ecosystem services, which emphasizes what we want the ecosystem to do for us, to also encompass how to support ecosystem functioning in agroecosystems designed after natural ecosystems and how to set priorities for land use amid competing interests. Focusing on ecosystem functioning rather than specific outcomes promotes continual improvement and is not tied to any specific agricultural practices, making it a useful approach for inspiring and guiding innovative transformation of all kinds of agricultural systems.

Enhancing ecological and social relationships in prairie ecosystems requires us to first understand how our existing realities came to be; we are well advised to “consult the genius of the place” (Pope, 1731) when making changes to our lands. The “genius” of a particular ecosystem lies within the key functions or outcomes it provides as well as the mechanisms that undergird its ability to perform these functions—its functioning. By peering into this web of relationships, we can learn to recognize where, how, and why ecological functioning has become compromised and then envision systems where ecosystem functioning is restored, identify potential pathways for restoring key processes and relationships, design and implement appropriate changes, and monitor progress. This process may require significant shifts in individual and collective relationships with each other and the land.

**Reframing human roles in agroecosystems**

Understanding the web of relationships in managed ecosystems begins with seeing humans as part of the ecosystem, not separate from it. In agroecosystems, local conditions and landscape features affect how farmers manage land and, in turn, farmers’ decisions affect ecological processes
(Benoit et al., 2012; Lovell et al., 2010). Priorities for ecological outcomes and the way these outcomes are achieved are shaped by social structures and human attitudes (Damhofer, 2021). Thus, the path toward restored ecosystems requires cultivating an appropriate set of human relationships with the land and with each other. Accordingly, we may ask: What are our individual and collective roles in local ecosystems? Whose goals are promoted in the overall approach to land use and in decisions regarding specific parcels of land? Whose voices need to be heeded when setting priorities for ecosystem management?

Looking to the prairie biome prior to European settlement, the relationship between humans and the land was deeply cultural and spiritual. Indigenous peoples actively managed the prairie landscape, even cultivating crops in localized areas (e.g. near Lockport, Manitoba, dating to the early 15th century (Flynn and Symns, 1996)). It is only within the last 150 years with European settlement that farming has dramatically changed prairie ecosystems. Today, we can only imagine how Indigenous land management would have evolved with advances in technology and other societal changes, since government policies and practices actively suppressed Indigenous agricultural development and took land away from Indigenous communities (Carter, 2019; Daschuk, 2013). Throughout recent efforts among Indigenous communities to rebuild their capacity in agriculture, especially using agroecological production methods, important pathways are being opened toward food sovereignty and reconnection with their culture (Arcand et al., 2020).

The colonial approach to settlement clearly had horrific effects on Indigenous peoples (Carter, 2019; Daschuk, 2013). The effects on settlers and their descendants, who now manage most of the land in the prairie region, are more subtle. In the late 19th and early 20th centuries, the Homestead Act and other immigration efforts brought a wave of settlers with a particular mindset: they were ready—and obligated—to establish farms quickly (Laforge and McLachlan, 2018). Bringing a worldview of human domination over nature and importing agricultural practices from their places of origin, many immigrant farmers scorned, disregarded, or were simply unaware of the traditional land management practices and general worldview of Indigenous peoples. Aided by rapid advances in mechanization and with only a short history on the prairie, it was probably easy for settler-farmers to see the transformation of native prairie habitats into swaths of cultivated farmland only as progress, without fully appreciating what was lost. For many descendants of settlers, their sense of place may be more closely tied to managed farm landscapes such as wheat fields or grazing cattle than to pre-settlement prairie ecosystems such as tallgrass prairie or roaming bison.

With growing awareness of and respect for Indigenous knowledge systems, farmers and other settlers may yet learn to adapt their worldview to local socio-ecological systems. What would prairie agricultural systems (and, indeed, our entire society) be like now if we saw the local flora and fauna as our kin? What would farm fields look like if we were all guided by the teaching of the honourable harvest, in which we take only what is freely given and offer our own gifts in return (Kimmerer, 2013)? How would research grant proposals differ if the target beneficiaries were the seventh generation into the future, as in traditional Indigenous decision-making processes (Haudenosaunee Confederacy, undated)? How such a shift in perspective will impact land management and agricultural practices in the prairie region remains to be seen, but it launches us along the path toward the twin processes of restoring human and ecological relationships.

Restoring prairie ecosystems also demands we integrate broader societal needs and priorities into decisions on land use. While farmers may sometimes feel powerless in the global food system, their control over large tracts of land under private land ownership structures gives individuals immense influence over ecosystem functioning, with impacts far beyond the borders of their farms. Those affected by local land use decisions range from neighbouring farmers and other rural residents to all global citizens, with the benefits and costs often borne by different members of society (Bennett et al., 2021).

Aligning land use with societal goals will require safe spaces for respectful and fruitful conversations among farmers and other actors as we work toward developing shared values. This process, too, requires transformation of worldviews. Even among prairie farmers, perspectives on appropriate land management vary widely, as seen in the often-polarized debates among organic and conventional farmers or large- vs. small-scale producers. Expanding the conversation to include the perspective of “consumers” (as if some humans do not play that role) is even more difficult, with public opinions on food production often seen as a display of ignorance at best or, at worst, a threat to modern farming systems. Re-establishing the relationships among those that manage the land and members of broader society requires attitudes of openness and trust, more likely to grow out of cooperative rather than competitive approaches. Heeding the voices of those who have historically been excluded from decision-making processes about land management, such as Indigenous peoples, newcomers, women, and youth, is not only essential for social justice but can also create innovative solutions that grow from a greater diversity of experiences and perspectives.

As part of the ecosystem, humans also participate in farm nutrient cycles, regardless of where they live or whether they are aware of it. In an increasingly urbanized society, nutrient cycles are necessarily stretched far beyond the local ecosystem as food is consumed far from where it
was grown. Reconnecting linear nutrient flows into partially closed loops via the circular economy is a priority for sustainable agriculture and is becoming more feasible with advances in nutrient recovery technologies and innovative use of “waste” products (Nicksy and Entz, 2021; Schneider et al., 2019; Withers, 2019). Greater public awareness of even this most basic biological human connection to the land may prompt citizens to engage more deeply with their food systems.

**Understanding prairie ecosystems**

From a biophysical standpoint, it is again instructive to consider how current ecosystems came to be. Native prairie ecosystems developed under conditions of scarcity. The relatively cold, dry climate of this region restricted decomposition and nutrient cycling rates, allowing the development of soils rich in organic matter. Ecological succession proceeded past the stage of herbaceous plants only when and where sufficient moisture and lack of disturbance permitted. These disturbances—mainly fire and grazing, both of which were guided by the activities of Indigenous peoples—produced short, localized bursts of biological activity. Nutrients released during these intensive events were quickly absorbed by the deep roots of a diverse mix of perennial plant species with extremely efficient nutrient use mechanisms. The inevitable downward movement of water (along with sediments and nutrients) through the landscape was generally slow due to the flat topography of the plains and the low degree of connectivity among the small water bodies of the prairie pothole region. Thus, native prairie ecosystems were characterized by processes generally following a restrained pace amid a great diversity of organisms with high nutrient and water use efficiency; a system of protective mechanisms absorbed occasional excesses arising from disturbance and synchronized resource availability and use.

With European settlement came an abrupt change in the nature and frequency of disturbance, as well as the structure of the landscape and the outcomes asked of it. In particular, the shift to simplified annual cropping systems accompanied by tillage and alteration of water flows via drainage prompted loss of biodiversity and increased the rate of nutrient cycling and water movement through the landscape. Harvesting agricultural products altered the relatively closed nutrient cycles of prairie ecosystems, depleting reserves of soil nutrients and organic matter and concentrating them elsewhere. Applying fertilizers or irrigation, or both, to previously nutrient- and water-limited grassland ecosystems relieved scarcities and shifted resource use dynamics in vegetation and soil microbial communities (Bradford et al., 2005; Schimel, 1986), at the expense of nutrient and water use efficiency. These developments, arising largely from an export-oriented agricultural economy, have further accelerated the pace and extended the geographic scale of nutrient cycling and water movement, creating linear flows rather than intact cycles, with ever more opportunities and routes for losses. The protective mechanisms to absorb such losses, once

provided by native vegetation and natural landscape features, have also been disrupted as agricultural activities have expanded through the landscape. Even in semi-natural areas such as native pastures, the patterns of disturbance created by grazing cattle differ from those of the fires and occasional herds of bison that shaped local ecosystems before European settlement. These changes have compromised the system of natural checks and balances and disrupted the synchrony among different ecosystem processes and components. While prairie ecosystems are remarkably resilient to a certain degree of change, the intensity and extent of prairie transformation has, in some cases, overwhelmed their capacity to perform their required functions.

Again, it is not too late to adapt our approach to land use to local prairie ecosystems. Looking to native habitats as a guide, we can aim to preserve, restore, or recreate key features of prairie ecosystems that lend them their resilience and integrity. This underlying ecosystem functioning will allow farm landscapes not only to adapt to environmental stresses and shocks but to evolve to meet changing human needs.

**Approaches to restoring prairie ecosystem functioning**

Efforts to restore ecosystem functioning in the prairie region require a multi-faceted approach, given the diversity of local conditions and priorities. Because ecosystem change is site-specific and unpredictable, we are well-advised to refrain from looking for the single best solution to a particular problem, choosing instead to use multiple strategies that aim for “the best chances of acceptable outcomes” (Lynch et al., 2021: 3) or that create opportunities to work toward a “desirable unknown” (Le Masson et al., 2019, as quoted in Prost, 2021: 3). Thus, rather than recommending best management practices, I describe several complementary avenues to explore, aiming to re-envision and redesign prairie farming systems by mimicking key aspects of natural ecosystems. Guided by the principles of biomimicry (Benyus, 2002), we can proceed to expand our knowledge on ecological and social dynamics in agricultural landscapes through research targeting ecosystem functioning in the context of prairie agroecosystems (Table 1), while already beginning to apply existing knowledge.

**Identify and understand interactions in agricultural landscapes**

The influences of social and biophysical components in the mixed natural and artificial landscapes of the prairie region create a web of interactions that affect ecosystem functioning and opportunities for restoration. In restoring agroecosystem functioning, it is particularly important to begin to understand the ability—and especially the *inability*—of the ecosystem to absorb or offset any negative effects associated with agricultural production. Such protective mechanisms need to be even more robust in agricultural
Design agricultural landscapes to support ecological functioning across space and time

Growing out of an understanding of ecosystem interactions, the goal of agricultural landscape design is to create the ecological infrastructure required to support effective functioning within the context of environmental and social realities. This approach seeks to harness and optimize ecological processes in farmlands to support productivity alongside other ecosystem services, a concept known as “ecological intensification of agriculture” (Tittonell, 2014). Spatial design of agricultural landscapes, sometimes called “farmscaping” (Smukler et al., 2010) or “landscape agronomy” (Benoît et al., 2012), involves the purposeful and strategic arrangement of agricultural activities and landscape features, a practice rarely employed outside the realm of permaculture (Ferguson and Lovell, 2014). The goal of such design is not generally to return the landscape to its pre-agricultural state, but to optimize landscape-scale ecological processes and outcomes in the agricultural system using natural systems as “mentors.” In a process not unlike human mentorships, inspiration from natural systems must be adapted and applied in the agricultural system in novel ways. For example, nutrient cycling in agricultural systems necessarily differs from local natural ecosystems, but the biomimicry principle of recycling can guide nutrient cycling approaches at regional rather than local scales, especially when supported by other nature-inspired principles such as reducing excesses and promoting diversity and cooperative relationships within the biotic community (Benyus, 2002; Mathews, 2011; Schneider et al., 2019). In this way, growing knowledge of natural ecosystem functioning can inform the design and management of specific landscape features to achieve the desired outcomes, even when—or perhaps especially when—such interventions differ from the original features of a particular parcel of land.

Using a spatially explicit approach to farm system design can help us tune land use to the local nuances of the landscape, considering soil properties, microclimate, field infrastructure, distance from the farmyard, and countless other factors (Benoît et al., 2012; Lovell et al., 2010). Identifying “weak links” in the landscape—those places where ecological processes are most compromised and contribute the most to environmental degradation—can point to interventions that will provide greatest potential benefits (Zimmerman et al., 2019). On the prairies, for example, we have a good understanding of nutrient loss pathways from fields to waterways (Baulch et al., 2019; Liu et al., 2013, 2019), which can guide the design and management of field margins and riparian zones (Habibiandehkordi et al., 2019). Still, many gaps remain in knowledge of how spatial dynamics affect ecosystem functioning in prairie landscapes. For instance, although we recognize the importance of natural habitats for beneficial organisms such as pollinators and pest predators (Morandin and Winston, 2006; Samaranayake and Costamagna, 2019), we know little about how field configuration and interactions among landscape features affect this and other scale-dependent processes within the prairie context, where fields are often very large.

Considering temporal dynamics can help to create landscapes with robust functioning across a range of time scales, from seasons to human generations. For example, keeping spring snowmelt runoff on the land as long as possible in seasonal wetlands can provide habitat for native species, improve groundwater recharge, and reduce nutrient losses to larger water bodies (Baulch et al., 2021). Long-term planning on a generational time scale can also include creative approaches to land use “rotation” within a farm or region, such as guiding ecological succession from annual crops to herbaceous perennials and then agroforestry, and perhaps eventually back to annual cropping, thus...
integrating social and ecological goals. This long-term perspective may be especially important in light of impending stresses such as climate change.

In certain parts of the prairie region, where few remnants of native prairie habitats are present, it will likely be necessary to remove some land from annual crop production to create a landscape design that meets production and environmental goals. Garibaldi et al. (2021) suggest that at least 20% of agricultural landscapes be devoted to original or restored native vegetation (perhaps under light human management such as grazing) to support ecosystem function and integrity, a target that may be difficult to reach in the most intensively farmed parts of the prairie region. However, by targeting less-productive land and weak links in the landscape, converting a small proportion of farmland to diversified perennial vegetation can contribute to disproportionately large benefits. For example, strategically placed perennial prairie strips in annual crop fields in Iowa dramatically reduced soil erosion and nutrient loss and enhanced biodiversity while occupying only 10% of the field (Schulte et al., 2017). In the Canadian prairie region, portions of the cultivated landscape to potentially convert to perennial vegetation include low-lying areas, water runs, field corners left by centre-pivot irrigation systems, field margins, and power-line rights-of-way. In areas with little marginal cropland and few remaining natural landscape features, farmers may need attractive incentives or other motivators to convert farmland to alternative uses.

When taking land out of annual crop production, restoring native habitats may provide the greatest environmental benefits and can also support harvesting of traditional foods and medicines as well as recreational uses. Other innovative land uses, such as small-scale diversified perennial forest gardens (Wartman et al., 2018), commercial-scale woody perennial polycultures (Kreitzman et al., 2021), or silvopastoral systems (Pent and Fike, 2021), can support economic activity while also providing a portion of the benefits of native habitats, if designed and managed with ecosystem functioning in mind. Such systems have seen very little research attention in the prairie region so far but can likely be adapted to a wide range of local conditions. Integrating these alternative land uses effectively into prairie ecosystems will require a better understanding of their strengths and weaknesses in promoting ecosystem functioning in various contexts, as well as the social and economic factors that contribute to their success (Kreitzman et al., 2021).

**Implement agroecological practices within croplands**

Using ecologically based crop production practices can improve ecosystem functioning within fields and thus support efforts in other parts of the landscape. Managing crops using agroecological principles and practices can, for example, enhance biodiversity, regulate nutrient cycling, and protect soil, sometimes without sacrificing crop yields (Altieri, 1999; Drinkwater and Snapp, 2007; LaCanne and Lundgren, 2018; Schipanski et al., 2014; Tamburini et al., 2020; Thiessen Martens et al., 2015). Despite their demonstrated benefits, we do not yet know how much such interventions can compensate for a lack of intact prairie habitat and landscape structure in supporting ecosystem functioning. Any incremental benefits from such cropping practices should, however, lessen the need for mitigation measures in other parts of the landscape. Crop production practices that improve ecosystem functioning within the borders of fields are particularly important for processes occurring at relatively small scales, such as gaseous nutrient losses and many pest dynamics, as well as in locations heavily dominated by annual cropland and large fields. Restoring ecosystem functioning within crop fields can support development of sustainable production systems on two fronts: reducing the need for products and practices, such as pesticides and tillage, that cause degradation and enhancing the ability of the ecosystem to recover from the disturbances required to maintain productivity.

Production systems that closely mimic the natural ecosystem, such as diversified perennial grains and forages, may offer the greatest ecological benefits (Bonin and Tracy, 2012; Malézieux, 2012; Ryan et al., 2018) but do not meet current human demand for annual crop products. A shift in demand toward products of perennial systems is worth pursuing, but improving annual crop production practices also remains a priority in both the near and long terms. In annual cropping systems, integrating features that mimic the diversity and perenniality of native prairie ecosystems, at least to some degree, may promote both adequate crop yields and elevated levels of ecosystem functioning (Sprung et al., 2020) and can be relatively easy for farmers to adopt. For example, growing more than one annual crop together in an intercropping arrangement can, to some extent, promote the mutualistic root interactions and pest suppression mechanisms that occur in diverse grasslands (Hinsinger et al., 2011; Hummel et al., 2009; Szumigalski and Van Acker, 2005). Mimicking the functioning of native habitats using annual crops requires insight into ecological processes occurring within crop fields, including nutrient uptake dynamics in polycultures (Hinsinger et al., 2011), synchrony of nutrient availability and demand over time (Kubota et al., 2018), effects of topography (Baulch et al., 2019), and the subtle, ever-changing mosaic habitat associated with seasonal farming activities (Fahrig et al., 2011; Vasseur et al., 2013).

Applying an ecological intensification approach within crop fields may involve purposefully altering ecosystem processes such as nutrient cycles, rhizosphere interactions, or predator–prey relationships to achieve specific outcomes (Andreasen et al., 2009; Hinsinger et al., 2009; Lemaire et al., 2014). Due to the web of relationships within ecosystems, manipulating one process may cause changes throughout the system, possibly introducing new risks of unintended consequences and requiring complementary changes to manage these risks. For example, grazing a legume-based green manure cover crop can increase total productivity and profitability by generating income from livestock products while preserving the nitrogen credit to following crops through accelerated decomposition of green manure plant residues (Cicek et al., 2015a; Thiessen Martens and Entz, 2011). But this accelerated decomposition rate can increase fall soil nitrate concentration, potentially posing a risk of leaching (Cicek et al., 2015b).
A fall catch crop may be grown after the grazed green manure to use excess soil nitrate, mitigating this risk (Cicek et al., 2015b). Accordingly, we must be mindful of the potential cascade of effects prompted by a single change and may need to design protective mechanisms into farming systems. Some authors propose that complex production systems, such as the no-till, integrated crop-livestock systems of southern Brazil, naturally self-organize to develop synergetic relationships, allowing soils to maintain synchronous nutrient flows and protect against losses (Anghinoni and Vezzani, 2021). The same may occur where planned biodiversity supports associated biodiversity and promotes the resulting benefits (Altieri, 1999). In such a scenario, human management would focus more on the design of the overall system, rather than specific interventions to micro-manage ecosystem functioning. How inherent ecological functioning may evolve within agricultural systems in the Canadian prairie context or elsewhere, through intertwined human management and ecological self-organization, is an intriguing question.

Preserve remaining native prairie habitats

Given the scarcity of undisturbed prairie ecosystems, including grasslands, parklands, wetlands, and riparian areas, and the difficulty of restoring degraded ecosystems to their original state, preserving existing native habitat remnants is a high priority. Native prairie ecosystems contribute to a sense of place and provide cultural value, while also harbouring a reserve of biodiversity to help restore surrounding areas. They can also serve as benchmarks for restoration efforts—not so much as defined targets, but as examples of how intact natural ecosystems respond to environmental changes. Characterizing and monitoring ecosystem properties in both farmlands and native habitats over the long term can help us understand how specific features of these systems contribute to specific outcomes.

Prairie remnants can help offset and absorb the negative effects of disturbances and excesses in the agricultural portion of the landscape and provide measurable benefits to cropland such as pollination services (Garibaldi et al., 2011; Morandin and Winston, 2006). Appropriate human management of native ecosystems based on Indigenous and scientific knowledge, through practices such as grazing, burning, and selective harvesting, is likely to help maintain their health and resilience and promote their ability to compensate for the effects of human management elsewhere in the landscape. An improved understanding of ecosystem functioning will provide direction for strategic management of prairie remnants, particularly in the face of altered successional trajectories due to climate change, ecosystem fragmentation, and interactions with the surrounding managed landscape.

Support sharing of knowledge and responsibility

While the benefits of sound ecosystem functioning in prairie ecosystems will flow to all members of society, it is farmers who will implement the necessary changes. Determining exactly what those changes ought to be is far from straightforward. The general goals of sustainability or resilience provide little guidance for the types of changes required or desired on a particular farm. Even with specific targets in mind, exactly what each farmer should or can do depends on local opportunities and constraints. A thorough understanding and sensitive discussion of the societal and personal values that shape what it means to be a “good farmer” (Laforge and McLachlan, 2018), along with participatory approaches such as collaborative research and co-design (Kröbel et al., 2021; Lovell et al., 2010; Moraine et al., 2016), are therefore essential in designing changes to farming systems. Perhaps even more important is a supportive peer group with whom farmers can share experiences and foster common values (Kreitzman et al., 2021).

Local and regional coordination among farmers and others can encourage collaborative ways of optimizing processes such as water and nutrient flows that occur at scales beyond individual farms (Lubell, 2004; Moraine et al., 2016). Creative partnerships can also diversify land use and provide meaningful opportunities to those who do not have easy access to land, such as newcomers and youth (Johnston, 2019; Lam, 2021). For example, inviting individuals or community groups to convert small parcels of land to forest gardens in key places in the agricultural landscape could help enhance both local food systems and ecosystem functioning (Wartman et al., 2018).

The process of implementing change in a farm system is rarely straightforward and linear. Rather, farmers tend to be “tinkers, engaged in an unfolding, open-ended process” (Damhofer, 2021: 3) of learning from experience, adapting to changing conditions and opportunities, and incorporating new information. Although this process may be slow, it attunes each farm system to its unique conditions and supports continual progress in the desired direction. Setting and revising that direction with human and ecological relationships in mind can lead to restored prairie ecosystems that meet current and future needs.

Targeting a balanced suite of outcomes that include environmental and social goals, rather than simply maximizing crop yields and minimizing costs, will require a shift in priorities for farmers, other citizens, governments, and industry alike. Transformative changes to land management, especially those that affect livelihoods and quality of life for farmers or others, require a “just transition” approach similar to that proposed for developing a low-carbon society (Natural Resources Canada, 2021). Support systems for farmers, including training, access to specialized equipment or other resources, and perhaps financial assistance, along with appropriate policies and legislation, will help ease the transition to alternative land uses. Though supports for ecosystem restoration come with a cost, the “cost of inaction is greater than the cost of restoration” (United Nations Environment Programme, 2021: 20) and the cost of early intervention is less than the cost of remediating advanced degradation. Having society bear some of the risks and financial costs of transformational
changes not only makes such changes more feasible, but also signals to land managers that their efforts to restore ecosystems are valued and may help reconnect urban citizens to the lands that sustain them.

Conclusions

Despite its productivity, the ecological integrity of the prairie region of Canada has been compromised through loss of native habitats, modified landscape structure, and soil degradation. These changes were driven, in part, by settlers’ and governments’ colonist attitudes toward the local peoples and ecosystems, along with technological advances, government policies, and the need to provide food for distant human populations. Thus, the path to ecosystem restoration lies in realigning these same forces to support a different approach to land use. Here, without delving into the realms of technology, policies, and markets, I have discussed how enhancing social and ecological relationships can help restore prairie ecosystems. In particular, paying attention to ecosystem functioning—the various interconnected processes supporting ecosystem functions or outcomes—will help continually improve the design and management of restored agricultural landscapes.

Restoring prairie ecosystems will require significant shifts in attitudes and land management practices but does not mean the complete abandonment of the agricultural practices that now dominate the landscape. Nonetheless, changes to annual production practices are unlikely to create the transformational changes required to remain within planetary boundaries; it will be necessary to transition a portion of the land currently in annual crop production to alternative land uses, such as diversified perennial crops or restored native habitats. Integrating social goals into the design of agricultural landscapes can spawn creative solutions but will require a shift toward a more open and collaborative approach, especially regarding the use of privately owned lands.

To support ecosystem restoration in the prairie region, research priorities will need to shift toward approaches that support healthy ecosystem functioning and perhaps away from maximizing yields in annual monocropping. We need not wait for complete understanding of the problems before beginning to explore solutions. Systems that improve ecosystem functioning and the outcomes that follow can already be investigated by applying known principles of agricultural production, biomimicry (Benyus, 2002), and ecological restoration (Gann et al., 2019), woven together with the experiential and traditional knowledge of farmers and Indigenous peoples. Additional basic and applied research in the natural and social sciences, along with transdisciplinary approaches that link social and ecological aspects of farming systems, will deepen knowledge of traditional and novel land use systems and biomimicry approaches. Considerable progress has already been made on certain research questions (Table 1) in some contexts, but is still lacking in others. We can also begin to implement existing knowledge at wider scales, recognizing that the approaches developed so far, while imperfect, can prompt movement in positive directions. Indeed, conservation groups and individual farmers are already leading the way in applying and adapting novel approaches to agricultural production, including agroecological production techniques and landscape-scale methods.

Restoring prairie ecosystems can be compatible with food-producing systems, though not quite as we currently know them. The path to restored ecosystems follows two intertwined transition processes: reorienting worldviews to embrace the social and biophysical contexts of local ecosystems, and taking practical steps to restore ecosystem functioning and integrity. Which begins first is perhaps less important than continually integrating the two, allowing the adapted worldview and novel practices to support and inform the other as they progress from infancy to maturity. In this way, “[w]e restore the land, and the land restores us” (Kimmerer, 2013: 337).

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