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Balancing Agriculture and Conservation in the Canadian Prairies

A *Research* Report prepared for CAPI by Ehsan Pashanejad

Research Report

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The Canadian Agri-Food Policy Institute's mission is to lead policy development, collaborate with partners and advance policy solutions within agriculture and food

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CAPI thanks our group of peer reviewers and the Advisory Committee for their feedback on earlier drafts of this report. The findings, interpretations, and conclusions in this report are solely those of its author.

Note from CAPI

CAPI recognizes the importance of fostering and mentoring the next generation of thought leaders emerging from Doctoral programs across Canada, who are working in multi-disciplinary fields. Through CAPI's Doctoral Fellowship program, CAPI offers a small, innovative group of young students the opportunity to apply their knowledge and expertise to some of agriculture's most critical policy issues.

The fourth cohort of CAPI's Doctoral Fellows (2024-2025) was tasked with focusing their research on policies needed to address pressures on Canada's land base and natural resources arising from agricultural production in the face of climate change, biodiversity loss, global population growth and food security concerns. This paper is the final deliverable of the program, showcasing the interdisciplinary nature of the fellows' research as it relates to mitigating trade-offs between conservation and intensive agricultural production on the Prairies.

This Fellowship is supported in part by the RBC Foundation through RBC Tech for Nature as part of CAPI's larger environmental initiative, Policies for Land Use, Agriculture and Nature (PLAN).

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Key Takeaways

- **Natural landscapes, particularly grasslands and wetlands, play a pivotal role in sustaining multifunctionality.** They are the primary drivers behind biodiversity conservation, water regulation, and carbon sequestration, even within intensively managed agricultural regions.
- **Key ecosystem services hotspots represent strategic zones for conservation investment.** The top 35% of landscape units—comprising about 19% of the Canadian prairies—account for more than half of key ecosystem services, while the remaining areas primarily support carbon storage, nutrient retention, and crop productivity.
- **Evaluating multifunctional landscapes in the Canadian prairies can guide more targeted land management interventions.** This can help policymakers and planners prioritize areas where ecosystem services can be protected or enhanced without undermining productivity. Future policies should build on this knowledge to support farm-level decisions and regional planning, aligning national commitments with practical actions on the ground.
- **Areas with high ES diversity are often characterized by a mix of natural and agricultural land uses.** They are ideal for aligning conservation and production goals. Incentive-based approaches like riparian buffers, agroforestry, and low-intensity farming can enhance service diversity while maintaining profitability.
- **Effective policy implementation depends on cross-sector collaboration.** Policymakers must engage farmers, Indigenous rights holders, researchers, and communities to co-develop practical, region-specific solutions that promote shared stewardship and sustainable outcomes.

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Glossary of Key Terms

Terms	Definition
Agroecosystem	*A human-managed specialized landscape where farming interacts with natural systems—includes fields, pastures, wetlands, forests, and the surrounding environment that supports them.*
Albedo	*The amount of sunlight reflected by the Earth's surface. Lighter-colored crops or cover types reflect more sunlight and can help reduce local warming*
α-Multifunctionality (Ecosystem Service Diversity)	*A measure of how many different ecosystem services (like crop production, pollination, and water regulation) are provided in the same area or unit. It shows the diversity of benefits from land.*
Biodiversity	*The variety of living species (plants, animals, and microbes) in an area. High biodiversity supports healthy ecosystems, crop production, and resilience to pests or climate extremes.*
Carbon Sequestration	*Carbon sequestration in agriculture refers to the process of capturing and storing atmospheric carbon dioxide (CO2) in soil and vegetation, effectively turning farmland into a carbon sink*
Cumulative Ecosystem Services Index	*A spatial score that adds up multiple ecosystem services in one place to show where overall benefits from nature are highest.*
Ecosystem Services (ES)	*The benefits we obtain from nature, such as clean water, fertile soil, pollination, flood control, and climate regulation.*
Habitat Fragmentation	*Breaking large natural areas into smaller, disconnected patches. This can reduce the ability of wildlife and ecosystems to thrive.*
Hotspots	*Areas that deliver very high levels of ecosystem services. In this report, hotspots are the top 35% of the landscape providing the greatest environmental benefits.*
Landscape Heterogeneity	*A landscape made up of a mix of different land uses and natural features (e.g., fields, forests, wetlands). Heterogeneous landscapes support a wider range of ecosystem services.*
Land-Use Intensification	*Farming more intensively by increasing the output (like food production) from a given land area, often by increasing inputs like fertilizer or expanding field sizes. This can impact natural systems if not managed carefully.*
Managed Landscapes	*Areas where land use is influenced by human activity, such as crop fields or grazing lands, often designed to support both production and ecosystem services*
Multifunctional Landscapes	*Landscapes that support both farming and nature—delivering food, income, and ecosystem services at the same time.*
Natural Climate Solutions	*Nature-based strategies like protecting grasslands, restoring wetlands, or planting cover crops that help reduce greenhouse gases and build climate resilience.*
Nature's Contributions to People (NCP)	*A broader term for ecosystem services, recognizing both the material and non-material benefits such education and recreational opportunities nature provides to humans.*
Soil Landscape of Canada (SLC)	*A national mapping system that divides Canada into landscape units based on soil, topography, and land use. Used as the basis for spatial planning in this report.*
Species at Risk (SAR)	*Plants or animals in danger of disappearing from part or all of their range. Many SAR in the Prairies depend on grasslands and wetlands.*
Spatial Optimization	*Using data and maps to find the best places to focus conservation or land management actions for the greatest benefit.*
Trade-Offs and Synergies	*A trade-off happens when improving one thing causes another to decline. A synergy is when two goals—like farming and conservation—benefit each other at once.*

Photo credit: Ehsan Pashanejad, Northern Prairies, Summer 2022

Introduction

The Canadian prairies are more than fields of wheat, canola, and cattle—they are dynamic living systems that store carbon, regulate water, and support biodiversity essential for the region's agricultural productivity and long term sustainbility. These ecosystem services (ES) or nature's contribution to people (NCP; Díaz et al. 2018) provide essential benefits that sustain human well-being, yet they are increasingly under threat from anthropogenic pressures such as land use change, habitat fragmentation, and resource extraction. In Canada, the total economic value of nature's contributions to people is estimated at $3.6 trillion per year (Molnar et al. 2021). For Prairie agriculture, this value becomes more tangible: grasslands for example, store vast amounts of carbon in their extensive root systems, making their conservation a critical climate change mitigation strategy (Nebel and Cook 2024). Studies (Olewiler 2004) show that the economic value of conserving and restoring natural habitats in agricultural landscapes in Canada ranges between $ 65 to 195 per hectare per year, through benefits such as nutrient retention, yield improvement, carbon sequestration, flood protection and many other services and goods generated by healthy ecosystems. Preventing the conversion of these habitats into croplands or urban areas is one of the most effective natural climate solutions available in Canada, with the potential to deliver significant carbon sequestration benefits over the coming years (Drever et al. 2021).

The Canadian prairies exemplify the challenge of balancing human activities with biodiversity conservation and protection and climate resilience. As one of the most modified landscapes in Canada, the prairies have lost more than 70% of its native grasslands to agricultural expansion. Despite this loss, the region remains critical for biodiversity conservation, as it hosts a significant number of species at risk (SAR); there are over 60 federally listed SAR) and provides essential ecosystem services such as carbon sequestration, water regulation, and pollination (Whitfield et al. 2024). Addressing these challenges requires integrated, evidence-based land management approaches that reconcile competing objectives. Global and national initiatives such as the Kunming-Montreal Global Biodiversity Framework (KMGBF; Diversity 2022) and Canada's 2030 Nature Strategy (Environment and Climate Change Canada 2024a)— set ambitious targets, including protecting 30% of land and restoring 30% of degraded ecosystems by 2030. However, translating these goals into practice on agricultural lands presents governance and implementation challenges. In Canada, agriculture is a provincial responsibility, and many provinces prioritize economic growth and agricultural intensification. This creates a policy disconnect between biodiversity commitments and local land-use decisions. At the same time, these frameworks open new opportunities—such as incentive programs, nature-based solutions, and climate-smart agriculture—that can align conservation goals with farm viability if supported by coherent cross-jurisdictional policy and strong partnerships with producers.

This report presents how nature and agriculture can work together on the same land. By using maps and spatial data such as land cover and land use layers, it identifies areas in the Canandian prairies where natural systems like grasslands and wetlands still provide important benefits for crop productivity such as pollinator habitat, nutrient retention, carbon storage, and soil erosion control while remaining compatible with productive farming. This is particularly essential to keep agroecosystems functioning and resilient. While resilience assessment is inherently complex, the message is simple: maintaining a mix of land uses and natural features— known as landscape heterogeneity—supports multiple ecosystem functions and their connectivity. This helps farmers adapt to climate impacts while remaining productive over the long term. By identifying critical hotspots for targeted management, this approach provides valuable insights into achieving multifunctional landscapes that balance conservation, production, and resilience objectives, contributing to more sustainable land-use planning and stronger ecological connectivity.

Background

The role of the Canadian prairies in ecosystem service provision and agricultural productivity

Stretching across Alberta, Saskatchewan, and Manitoba, the Canadian Prairies form the backbone of the country's agricultural landscape, accounting for more than 80% of Canada's cultivated farmland. This region is integral to Canada's economy, contributing 21.6% to the national GDP in 2020 and experiencing a 340% GDP growth over the past three decades (Government of Canada 2021). While agriculture constitutes a smaller share of this total, it plays a crucial role in food security and sustainable land management. The Prairie region is a key producer of wheat, canola, cattle, and hogs, generating aproximately $29.7 billion from these four commodities alone, which accounts for the vast majority (approximately 65.2%) of Canada's total farm revenue in these sectors (Agriculture and Agri-Food Canada 2024).

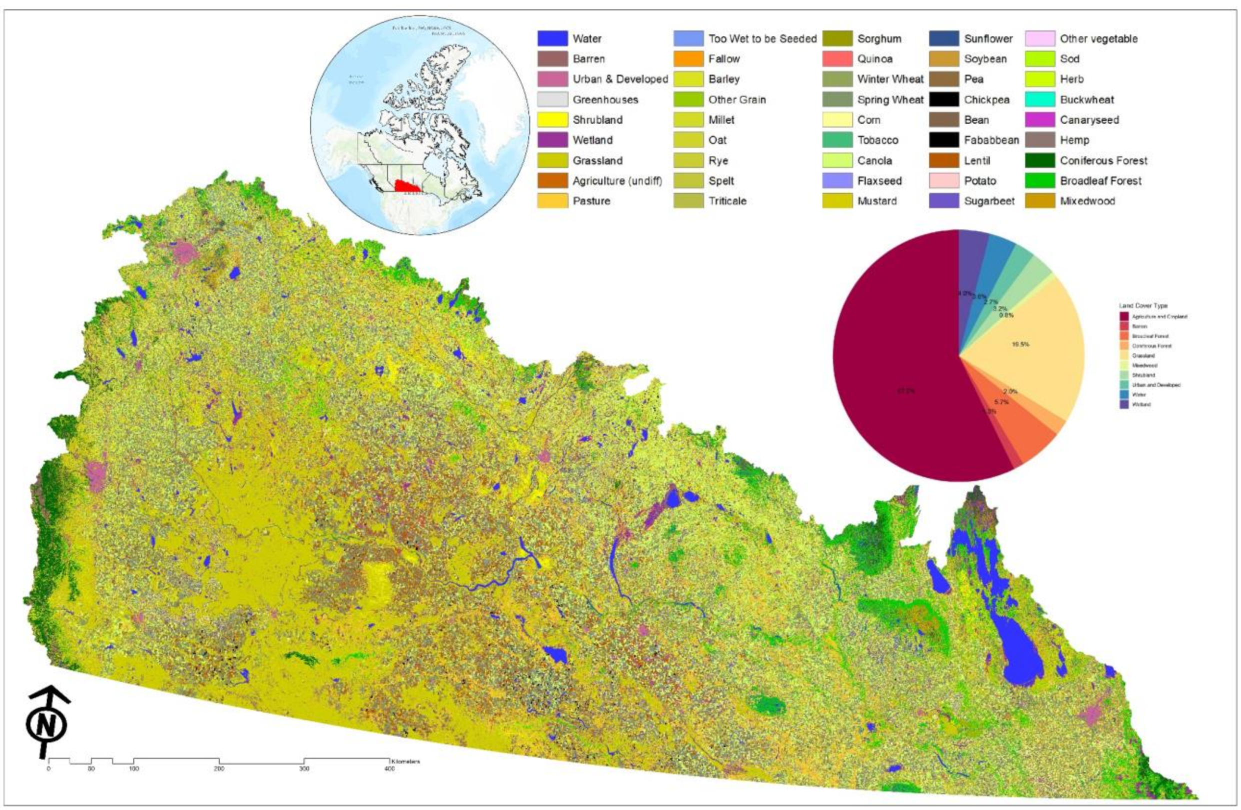

*Figure 1. **Geographic location of the study area and land cover/land use map of the Canadian Prairies,** highlighting landscape transformation from the Rocky Mountains in Alberta (west) to Manitoba (east). Grasslands dominate approximately 20% of the landscape, primarily in the southern to central parts of Alberta and Saskatchewan. Coniferous forests are concentrated along the western edge of Alberta, near the boundary of the study area. Agricultural activities and croplands are the most extensive land use type, accounting for more than 50% (including annual and perennial crops) of*

the total area. Land cover data is sourced from the 2020 annual crop inventory dataset produced by Agriculture and Agri-Food Canada (AAFC).

Despite the economic importance of agriculture in the prairies, increasing land use intensity—such as expanding field size, removing natural habitat and buffers, wetland drainage, and converting marginal lands—has led to significant environmental degradation. Wetland drainage and grassland conversion have disrupted water flow, reduced water quality, and accelerated biodiversity loss across the region (Baulch et al. 2021). While natural factors historically shaped the prairie ecosystem, including periodic wildfires and the presence of bison (*Bison bison*), today's land use practices, including cattle grazing and large-scale crop cultivation, and infrastructure development are the dominant forces influencing both farm practices and ecological health. (Paterson et al. 2024). Even though some practices like cattle grazing have historically been viewed as drivers of ecological change, emerging research and collaborative efforts increasingly recognize that well-managed grazing can help maintain grassland biodiversity and replace some of the ecological functions once performed by bison. Nonetheless, the ongoing and historic loss of natural habitats remains a leading driver of biodiversity decline in this ecozone (Bartzen et al. 2010; Olimb and Robinson 2019) .

Multifunctional land management for resilient landscapes

Multifunctional land management refers to designing and managing landscapes in ways that deliver multiple outcomes from the same area of land. This approach is gaining traction in land management as a strategy for balancing agricultural productivity with ecosystem sustainability in regions like Canadian prairies. While large-scale specialization and homogenization in production systems (Nyström et al. 2019) can maximize short-term productivity (Peterson, Eviner, and Gaudin 2018), it often leads to environmental externalities such as soil degradation, biodiversity loss, and decreased resilience (Frei et al. 2020). In contrast, multifunctional landscapes, where agricultural productivity coexists with ecosystem functionality, can provide a suite of benefits, including soil carbon storage, pollination, water quality regulation, and recreational services. Research suggests that landscapes exhibiting higher multifunctionality support both agricultural and biological diversity, promoting resilience across spatial and temporal scales (Gaba and Bretagnolle 2020). However, a social-ecological lens is essential for understanding the mechanisms that enable multifunctionality. By aligning land use practices with ecological processes, it is possible to create synergies that reinforce food security and farmer livelihoods while ensuring biodiversity conservation.

Results

Hotspots of ecosystem service multifunctionality

Our analysis shows that a relatively small share of the prairie landscape —just~19%— delivers the majority of key ecosystem services like pollination, soil erosion control, and habitat quality. These high-performing areas, or "hotspots" herein, play a critical role in sustaining natural systems that support agriculture. For instance, they contribute approximately 57% of soil erosion control, 57% of habitat quality, and 42% of pollination services, emphasizing their critical role in maintaining ecosystem functions. It is worth mentioning that the remaining portion of the landscape (that is not recognized as an ES hotspot) supports the majority of carbon storage, nutrient retention, and crop productivity (~98%), underscoring the importance of broader landscape-scale management to sustain these services (Table 1). Within these high-value ES provisioning areas, grassland dominates the multifunctional landscape, accounting for over half of the top 35% areas, highlighting their significant role in sustaining ecosystem functions and biodiversity. Similarly, wetlands and shrublands contribute significantly to water regulation, carbon storage, and habitat quality. Forested land types (broadleaf, coniferous, and mixed wood) collectively make up around 23% of the top multifunctional areas, indicating the critical role of maintaining forested patches in sustaining prairie ecosystem services. Agricultural and cropland areas, on the other hand, cover only a small fraction of the cumulative (which sums standardized ES values per unit; see Methods) ES provisioning area while covering an extensive area of the prairies landscape (Figure 3). Our results demonstrate that natural landscapes and ecosystems, and especially wetlands and grasslands, are key contributors to ecosystem service provisioning in the prairies (refer to the box plot, panel c in Figure 3).

Practically speaking, the cumulative ES provisioning index identifies areas where targeted conservation investments such as protecting native grasslands or restoring wetlands can yield the highest returns in total ecosystem service supply. These are priority zones for ecosystem service conservation, where focused efforts like habitat protection, ecological restoration, or agri-environmental incentives can deliver disproportionately high ecological benefits. For instance, Baulch et al. (2021) emphasize the critical role of wetland restoration in improving water quality and nutrient retention, reinforcing the value of conserving ES-rich landscapes. Identifying and safeguarding these zones is essential for aligning agricultural land-use planning with Canada's broader biodiversity and climate goals.Conversely, ES diversity index (α-multifunctionality; see Methods) provides different perspectives accounting for the diversity of ES per unit area, regardless of their magnitude. This index in fact reveals where high-value ES provisioning units or pixels on the map are more spatially dispersed and are driven by diverse land uses and cover types rather than a single dominant service. Although they may not rank highest in total service supply, these landscapes offer a unique opportunity to support multiple objectives simultaneously, including food production, climate regulation, and biodiversity conservation. This makes them ideal candidates for integrated land management strategies. For example, the adoption of riparian buffers and agroforestry practices has shown promise in enhancing service diversity while maintaining agricultural viability. Rallings et al. (2019) demonstrate that implementing riparian buffers and hedgerows in intensively farmed landscapes like the Lower Fraser Valley in British Columbia can enhance landscape multifunctionality, improving habitat connectivity and ecosystem services while minimizing loss of productive farmland.

We analyzed the diversity of ES provisioning in the prairies under two scenarios where first we explored the index variability in natural landscapes in the absence of croplands (Figure 4 panel a, c), and second, we explored the diversity of ES in managed landscape including cropland. Interestingly, cropland areas play a significant role in driving α-multifunctionality due to the inclusion of crop productivity, nutrient retention, soil erosion control and in some cases a moderate level of carbon sequestration when they were included in the index calculation (Figure 4 panel b). Box plots indicate ES diversity tends to be higher in wetlands, grasslands and forest in the first scenario (panel c, Figure 4), whereas panel f (Figure 4) highlights the substantial role of agriculture and crop provisioning that contribute to the overall ES diversity (α-multifunctionality index). Notably, agricultural landscapes show high diversity due to intensive provisioning services that may overshadow the diversity of natural systems. Forest-dominated landscapes such as those in western part of the study area or natural grassland in places such as the central part of Alberta dominate cumulative ES hotspots and appear less significant in α-Multifunctionality due to lower diversity in service types per pixel that is also due to landscape heterogeneity.

Table 1. Analysis of ecosystem service provisioning within the top 35% multifunctionality areas in the Canadian Prairies. These areas, identified based on cumulative ecosystem service index, disproportionately contribute to landscape-scale ecosystem service provisioning.

Ecosystem Service	Category	Area (km²)	Mean Value (Per Pixel)	Contribution to Total ES (%)
Pollination	Top 35% Hotspots	10,626	0.744	41.94
	Remaining 65%	43,662	0.251	58.06
Carbon Storage	Top 35% Hotspots	10,626	0.582	21.74
	Remaining 65%	43,662	0.664	78.26
Nutrient Retention	Top 35% Hotspots	10,626	0.034	5.11
	Remaining 65%	43,662	0.154	94.89
Habitat Quality	Top 35% Hotspots	10,626	0.945	56.96
	Remaining 65%	43,662	0.174	43.04
Avoided Erosion	Top 35% Hotspots	10,626	0.002	57.34
	Remaining 65%	43,662	0.0004	42.66
Crop productivity	Top 35% Hotspots	1,179,659	0.0195	1.46
	Remaining 65%	4,850,107	0.321	98.54

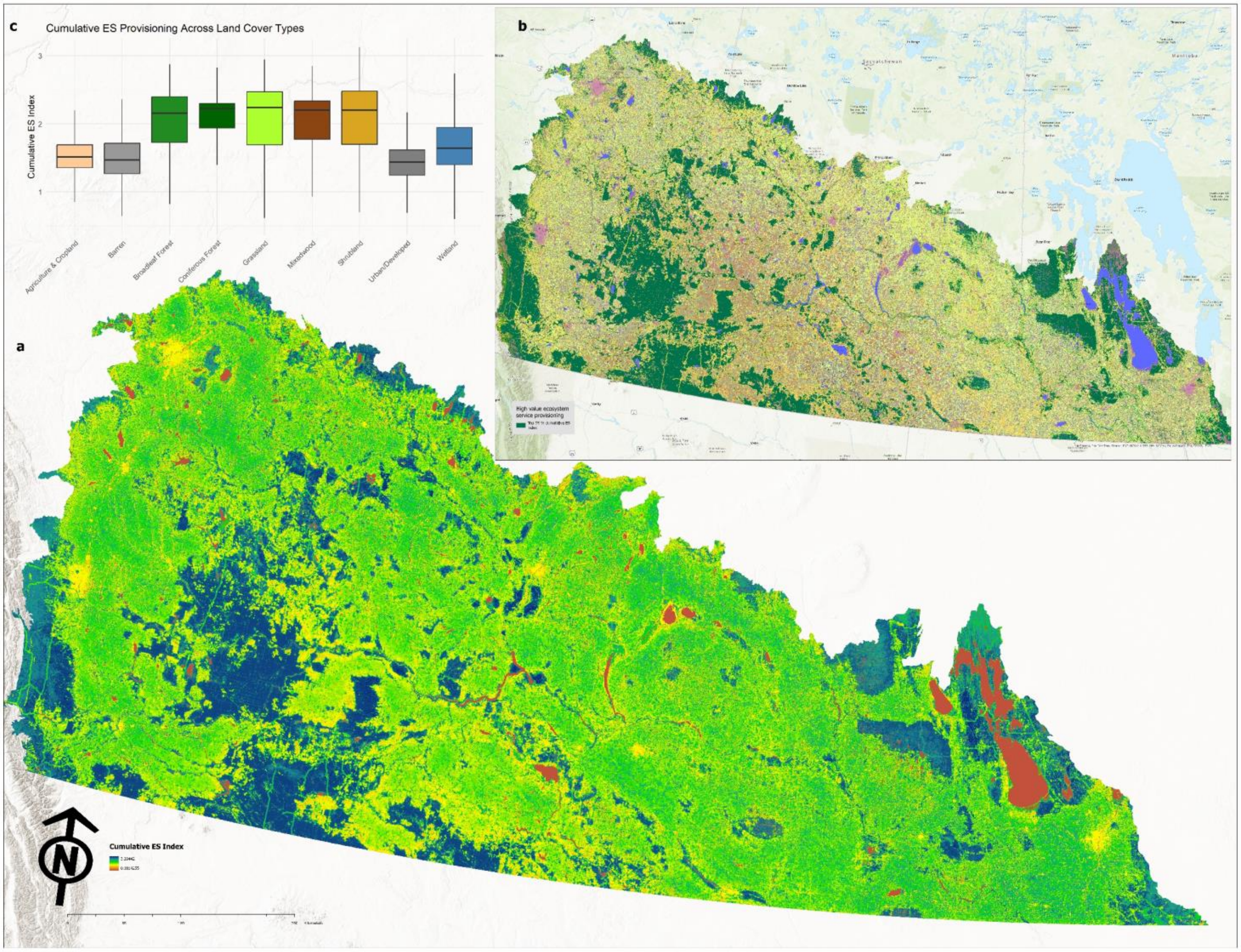

Figure 2. ***Spatial and statistical representation of cumulative ecosystem service provisioning across the Canadian prairies***. **Panel (a)**: Spatial distribution of the Cumulative ES Index. The intensity of blue color shading represents areas with higher cumulative ES values, indicating zones of high ecosystem service supply. Hotspots of cumulative ES are represented in **panel (b) Panel (c):** Box plot of cumulative ES provisioning across land cover types, illustrating the contribution of different land cover classes to the cumulative ES supply**.** Natural ecosystems (e.g., wetlands, grasslands, forests) exhibit higher ES contributions compared to agricultural and urban areas, reflecting their essential role in sustaining ecosystem functionality. The top 35% ES hotspots offer a targeted approach for conservation prioritization, ensuring that high-functioning landscapes are preserved.

Table 2. Land Cover Composition in Top 35% High-Value Multifunctionality Areas. Land cover types within the top 35% multifunctionality areas, highlighting the dominant contributors to ecosystem service provisioning.

Land Cover Type	Area (km^2) in ES multifunctionality	Total Area in the landscape	% of Total ES Areas	Proportion of Land Cover Type in Top 35% Relative to Whole Landscape (%)
Water	741.15	19514.44	0.70	3.80
Exposed Land/Barren	957.6	7277.545	0.90	13.16
Urban/Developed	568.44	14546.11	0.53	3.91
Shrubland	9085.95	17553.64	8.55	51.76
Wetland	3458.52	21564.31	3.25	16.04

Grassland	62080.29	106137.8	58.42	58.49
Pasture	2876.04	49427.69	2.71	5.82
Agriculture & Cropland	1342.17	262946.4	1.26	0.51
Coniferous	6430.86	11110.12	6.05	57.88
Broadleaf	16086.24	31079	15.14	51.76
Mixed wood	2631.6	4495.4	2.48	58.54
Total	**106258.86**	545652.4	**100**	**19.47**

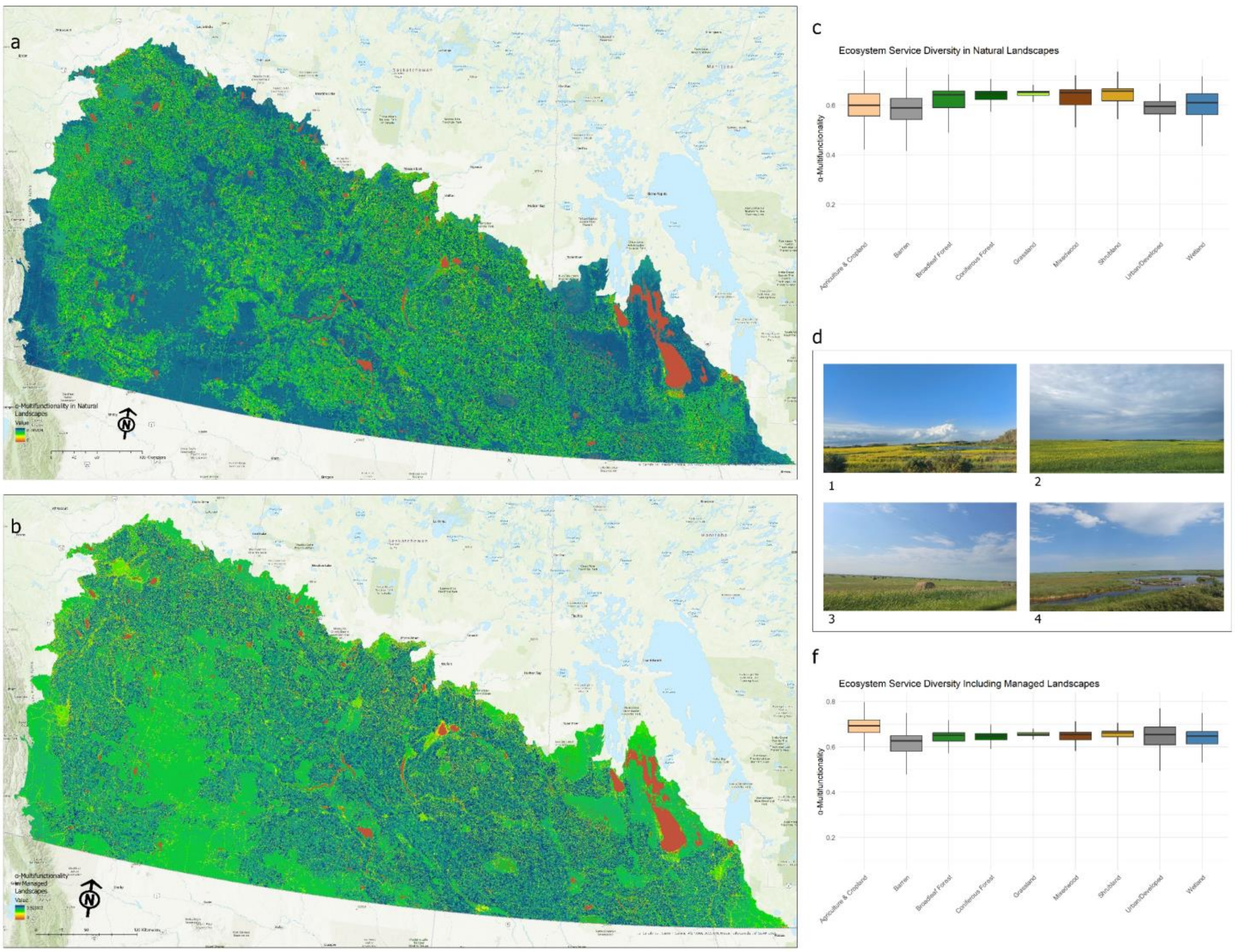

Figure 3. **Spatial patterns and statistical analysis of ecosystem service diversity represented by α-Multifunctionality indices across the Canadian Prairies under two scenarios. (a)** natural landscapes and **(b)** managed landscapes, including cropland. **(c)** Box plots illustrating α-multifunctionality (ES diversity) in natural landscapes across major land cover types**. (f)** Box plots of ES diversity including managed landscapes, highlighting the influence of agriculture and cropland on ES diversity patterns. **(d)** Field photographs taken during a summer 2022 field trip depict key landscape types: (1) & (2) cropland-dominated areas with natural habitat

inside the agriculture mosaic, (3) grassland-cropland transition zones and managed grasslands, and (4) wetland habitats (Oak Hammock Marsh, Manitoba).

The Spatial interactions of cumulative multifunctionality with ES diversity(α-multifunctionality)

Figure 4 illustrates the spatial overlap between cumulative ES provisioning and α-multifunctionality index based on the managed landscapes scenario. This bivariate map highlights clear hotspots where both overall ES supply and service diversity meet each other. It offers a decision-support tool to identify synergies and trade-offs in landscape management. These areas function as dual-benefit landscapes, delivering multiple ecosystem services while maintaining land productivity. The synergistic relationship represents strategic zones of alignment where ecological and agricultural goals reinforce each other. Such areas are critical for advancing Canada's commitments to biodiversity, climate resilience, and sustainable food systems. From a policy perspective, these landscapes offer high-impact opportunities—where targeted investments in conservation or agri-environmental programs can yield the greatest co-benefits across multiple sectors. Put simply, these are places where protecting nature also supports productive land—Canada's best opportunity to get both right.

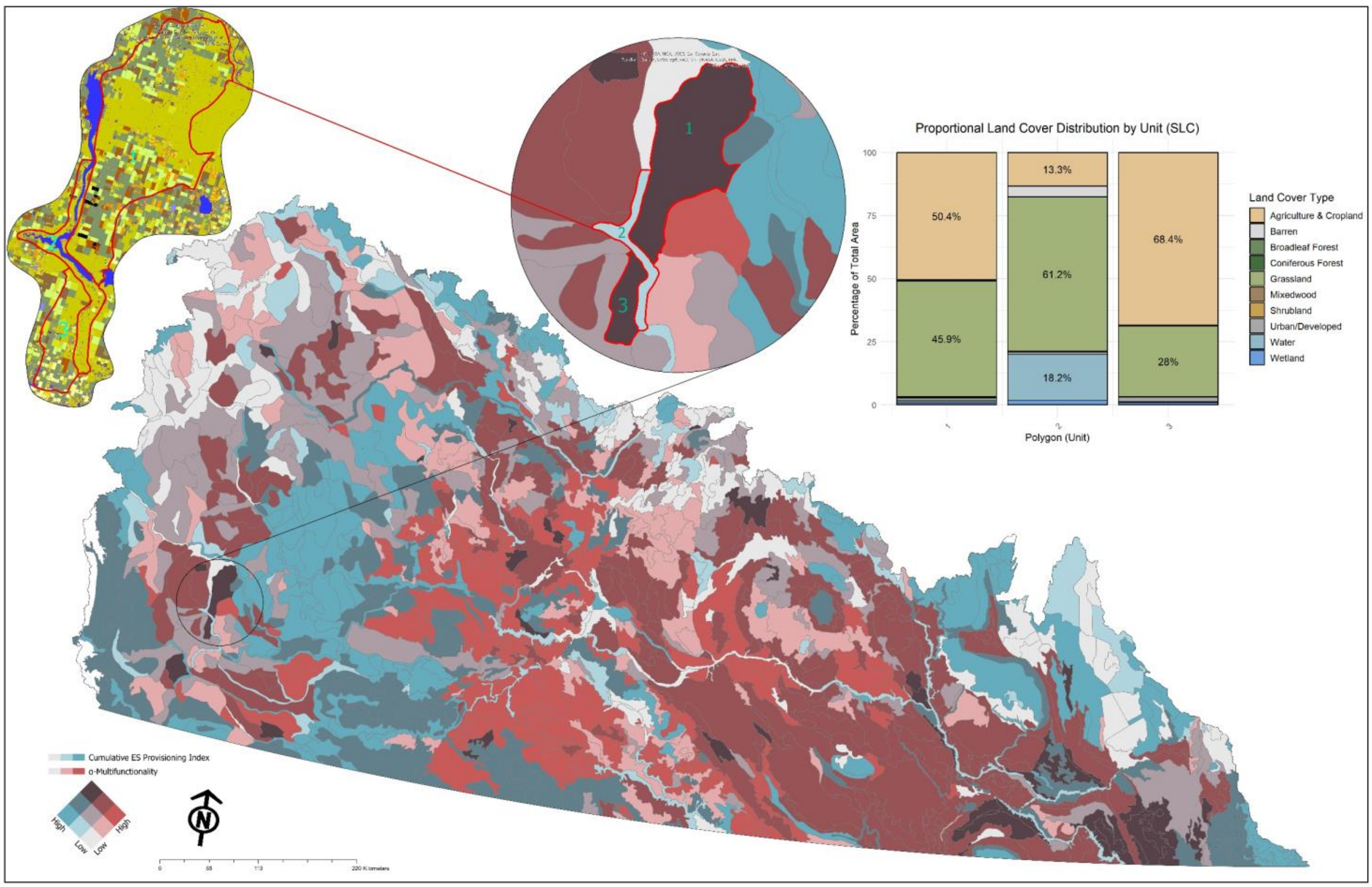

Figure 4. **Bivariate map of cumulative ecosystem services (ES) provisioning index and α-multifunctionality index**, aggregated by Soil Landscape of Canada (SLC) units under a managed landscapes scenario. Areas with high cumulative ES (light blue) and high multifunctionality (light red) are shown separately, while overlapping purple zones indicate regions where both indices are high. A complementary stacked bar chart illustrates the land cover and land use distributions within selected SLC units. Notably, units 1 and 3 display a balanced mix of natural habitats and other land uses—with unit 3 having at least 30% natural land cover and unit 1 over 45%—demonstrating harmonization between landscape diversity and ES provisioning. In contrast, unit 2, despite high

cumulative ES, is dominated by natural land cover (61.2% grassland) with minimal agricultural presence (13.3%), highlighting the trade-offs inherent in multifunctional landscape management.

Our results highlight that natural ecosystems, such as grasslands and wetlands, dominate high-value ecosystem service provisioning areas, underscoring their essential role in maintaining biodiversity and ecosystem functions. This is supported in a similar study conducted in the prairies by Paterson et al. (2024) who demonstrate that maintaining a minimum of 20% natural habitat within agricultural landscapes can safeguard a substantial proportion of regional biodiversity. These results suggest that effective landscape configuration is closely correlated with enhanced ecosystem service provisioning in multifunctional landscapes. Furthermore, bottom-up approaches—such as the adoption of on-farm best management practices—can significantly boost both productivity and conservation, thereby delivering multiple ecosystem services. For instance, reduced fertilizer and lower mowing frequency, has been shown to enhance cultural and regulating ES such as biodiversity conservation and nitrogen retention (Richter et al. 2024). Studies have also shown that integration of hedgerows and riparian buffers in agricultural landscapes maximizes multifunctionality by addressing trade-offs among ecosystem services, biodiversity conservation, and agricultural production. However, achieving this balance requires strategic planning, understanding farmer behaviour and developing policy incentives to offset the opportunity costs of reallocating productive land (Rallings et al., 2019).

Assessing the multifunctionality of ecosystem service provisioning in the Canadian prairies is a critical first step in exploring how to mitigate trade-offs between conservation and intensive production systems—especially given that this region contributes significantly to the nation's agricultural output, accounting for more than 20% of the national GDP considering all sectors. Previous studies have emphasized the critical role of multifunctional landscapes in sustaining nature's contribution to people at a global scale (Chaplin-Kramer et al. 2022; Neugarten et al. 2024), yet the present study advances this understanding by localizing ecosystem service multifunctionality. Using spatial indices, such as ecosystem service diversity (α-multifunctionality; (Simion et al. 2023)), and integrating ES mapping, we provide a guiding framework for policymakers and landscape managers to identify trade-offs and synergies in agroecosystems. These analytical tools pave the way for more targeted interventions—such as developing spatial optimization models and scenario-based analyses to delineate specific land-use configurations that maximize individual ecosystem services while quantifying thresholds beyond which intensification may compromise biodiversity, and through detailed mapping of ecosystem service hotspots to identify priority areas for conservation that complement agricultural production. We recognize that these strategies represent broad intervention pathways; future analysis should integrate more in-depth needs and values of different stakeholders, rights holders, and landowners into the decision-making and optimization process, ensuring that diverse perspectives are considered in aligning global biodiversity goals with local and national food production demands and allowing for targeting of interventions considering individual farmer behaviour and regional differences.

The spatial indices, tailored for landscape-scale assessments, align with the concept of scale dependence in multifunctionality evaluations by aggregating ecosystem service provisioning across Soil Landscapes of Canada as potential planning units, offering a regional perspective on multifunctionality. The cumulative ES provisioning metric represents pattern-based multifunctionality by identifying spatial hotspots of service supply, while α-multifunctionality bridges toward process-based multifunctionality by capturing the diversity of services and their ecological interactions, reflecting the complexity within landscape units. By integrating α-multifunctionality with trade-off analyses, we explore the existence of functional relationships between production systems and conservation, providing insights into how different ES interact.

In this study we combined spatial indices of multifunctionality to explore ecosystem service diversity and the landscape capacity delivering multiple services. This helped us to explore how different land cover and land use types contribute to balanced service provisioning within a unit (SLC, refer to Figure 4 and inset map of land cover configuration in three random selected units). The analysis of land cover composition in ES multifunctional areas indicates the critical role of natural habitats within agricultural landscapes, with more than 50% of these areas—comprising shrublands, grasslands, and various forest types—making significant contributions to high-value ecosystem service provisioning, as identified within the top 35% by the cumulative ES index.

Using multifunctionality metrics, we identified areas with the highest overall ES capacity and regions where production and ecological functions intersect. While the cumulative ES provisioning index identifies areas with the highest capacity for ES delivery and indicates the total supply of all ES in a given unit, α-multifunctionality pinpoints regions where diverse sets of ES coexist. In our analysis, each service was treated with equal weight, meaning this index captures service diversity rather than prioritizing one type over another. However, in practice, the importance of these services may vary by region or goal. This index serves as a starting point for identifying multifunctional areas that could support both conservation and agriculture, with further room for refinement based on local priorities or policy needs. The analysis also revealed that regions with high ES diversity often face competing demands between conservation and production objectives.

To effectively inform policy decisions, we employed two analytical scenarios for assessing ecosystem service diversity (α-multifunctionality). The scenarios were explicitly selected to demonstrate how agricultural management influences landscape multifunctionality: (1) Natural landscapes—assesses ecosystem service diversity without agricultural land use, highlighting the inherent multifunctionality potential of natural ecosystems. This scenario informs policy decisions on where conservation and restoration might deliver high ecosystem service benefits independent of agricultural management. (2) Managed landscapes—incorporates agricultural lands into the analysis, capturing the role agriculture plays in providing key provisioning services (such as crop productivity) alongside regulating and supporting services. This scenario provides policymakers with realistic insights into managing landscapes where agriculture is integral to local economies and farmers livelihoods. It is important to note that these scenarios are not meant to represent policy extremes (i.e., complete conservation versus full-scale agricultural homogenization). Instead, they provide complementary perspectives that enable a balanced understanding of conservation objectives alongside agricultural productivity in multifunctional landscapes. By adopting a transformative approach, we suggest that trade-offs associated with agriculture can be mitigated through the adoption of effective, sustainable, and resilient farming practices, which will require different interventions depending on individual farmer preferences. While this may appeal to early adopters, we acknowledge that some farmers may be more hesitant to change. Thus, flexibility is essential not only to support innovation among forward-looking producers but also to ensure that policy design remains inclusive and responsive to diverse needs. A sound policy for sustainable agricultural landscapes should align national biodiversity and conservation commitments with on-the-ground realities of Canada's varied farming communities .

Given that Canada's food security is deeply reliant on the prairie agroecosystem, these landscapes should be recognized as strategic opportunities to bolster food security while advancing climate mitigation and biodiversity conservation efforts. For instance, research in the Canadian prairies has shown that agricultural land management practices can significantly alter surface albedo—defined as the fraction of incoming solar radiation reflected by the Earth's surface—which in turn influences local climate patterns, energy balance, and radiative forcing. Studies by Liu et al. (2021, 2022) indicate that replacing summer fallow with cover crops and adopting reduced soil tillage can enhance climate change mitigation effects. Over a 50-year timeframe, the transition from conventional tillage to no-till farming resulted in a CO_2-equivalent reduction of 1.0–1.5 kg m^{-2}, while replacing summer fallow with actively growing crops yielded a reduction of 1.1–2.4 kg m^{-2}. Furthermore, crop type selection also plays a role in modulating albedo. For example, the expansion of annual crops such as lentils, peas, and canola—known for higher surface reflectivity compared to cereal crops like wheat and flax—can contribute to increased regional radiative cooling (Liu et al. 2022). Similar studies in the United States and Europe have demonstrated that management strategies, including perennialization, can enhance surface reflectivity and provide additional ecosystem services such as nutrient retention and carbon sequestration (McDaniel et al. 2023; Scott et al. 2022; Shang et al. 2024). Overall, these findings suggest that strategic land management practices—such as perennialization, conservation tillage, and reduced summer fallowing—can yield co-benefits for soil carbon sequestration and climate mitigation by simultaneously increasing surface albedo. This dual-benefit approach emphasizes the need for policies that promote adaptive and integrated management regimes to reconcile the objectives of agricultural productivity with environmental sustainability.

Policy Implications

The Canadian prairies are not just the bread basket of Canada to feed us, they are also one of Canada's opportunity and natural tools for climate action and biodiversity protection. However, realizing this dual potential depends on maintaining the ecosystems that underpin both agricultural productivity and environmental resilience. Prairie agroecosystems are home to a wide range of ecosystem services from carbon storage and water regulation to pollination and soil retention that support food production and climate stability. It is worth mentioning that effective conservation in this region requires coordinated efforts between federal, provincial, and local governments and Indigenous communities, especially under Canada's governance system where jurisdiction over land and natural resources is shared. While federal frameworks like the Species at Risk Act(SARA) set national goals, implementation often depends on provincial cooperation, creating both opportunities and challenges. For example, the Prairie Habitat Joint Venture and provincial Prairie Conservation Action Plans (PCAPs) offer encouraging models of collaboration, aligning agricultural and conservation goals. Strengthening intergovernmental cooperation and harmonizing conservation tools across jurisdictions would improve outcomes for both biodiversity and agricultural landscapes.

By exploring high-value ecosystem services at the landscape scale, we can navigate spatial dynamics and identify dominant trade-offs between ecological integrity and economic performance. Understanding where, and how ecosystem services matter for agriculture allows us to pinpoint spatial patterns that reflect both ecological significance and the economic functions of specializing agricultural activities. The insights from this analysis can inform policy options aimed at enhancing the connectivity of key ecosystem services and fostering multifunctionality. Below, I highlight several potential policy pathways that position prairie agroecosystems as strategic opportunities for sustainable development in Canada.

Leverage agroecosystems as climate mitigation assets: recognizing agroecosystems as strategic opportunities rather than environmental liabilities. By integrating sustainable management practices, policymakers can harness the dual benefits of agricultural landscapes, transforming them into tools for regional climate regulation and biodiversity conservation.

Promote integrated, sustainable farming practices: encourage targeted policies that support content-appropriate practices such as no-till farming and conservation tillage to reduce soil disturbance and improve moisture retention, cover cropping to enhance soil fertility and prevent erosion, and perennialization (e.g., using deep-rooted perennials or agroforestry buffers) to sequester carbon and stabilize landscape. These methods not only maintain or enhance crop productivity but also boost ecosystem services—such as increased surface albedo and carbon sequestration—thereby supporting both food security and climate and biodiversity loss mitigation goals.

Incentivize multifunctional land management: developing targeted policy instruments such as agri-environmental payment schemes, performance-based subsidies, or outcome-linked stewardship contracts that reward landowners for adopting practices which sustain multiple ecosystem services. These mechanisms should go beyond traditional payment for ecosystem services (PES) by effectively offsetting the trade-offs associated with intensive agri-food production—ensuring that producers recognize such measures as essential. For example, policies could include reframing national and local supply chains to favour conservation-valued products or targeting markets that prioritize sustainability, even in the absence of direct financial incentives. These efforts must be complemented by strategies that build consumer awareness and willingness to pay, as market uptake ultimately depends on demand for sustainability attributes. In addition, traditional tools—such as financial incentives, tax breaks, or grants—remain vital for promoting practices that enhance soil health, water quality, and biodiversity while maintaining agricultural productivity as long as farmers' risk behaviour and bottom line encourage them to do so. To ensure fairness and fiscal responsibility, these programs should prioritize actions that generate measurable environmental benefits and would not otherwise occur without public support. This helps catalyze genuine transformation rather than subsidizing business-as-usual.

Enhance agroecological practices: promoting integration of agroforestry, riparian buffers, and hedgerows into agricultural landscapes to reduce fragmentation, improve water quality, and support habitat connectivity. These bottom-up measures can help mitigate environmental impacts while enhancing ecosystem service diversity.

Align policy frameworks with multifunctional objectives: revising existing agricultural and environmental policies to reconcile economic growth with conservation priorities. Policies should encourage multifunctional land use that simultaneously delivers high crop yields, preserves natural habitats, and enhances overall ecosystem resilience.

Foster cross-sector collaboration and innovation and their investments: developing multi-stakeholder and rightsholder platforms that bring together farmers, researchers, environmental agencies, and local communities to conduct research that will be readily adopted by farmers given their unique preferences and situations. This will drive the adoption of adaptive management practices that balance agricultural productivity with environmental sustainability, ensuring a resilient agroecosystem framework.

Method

The methods used in this study comprise two main steps. First, we quantified and mapped key ecosystem services in the study area using the InVEST modeling tool (Sharp et al. 2014). Second, we developed and applied two spatial indices—cumulative multifunctionality and α-multifunctionality (Simion et al. 2023)—derived from individual ecosystem service maps. These indices were assessed under two scenarios: (a) natural landscapes and (b) managed landscapes, including croplands. Spatial patterns of ecosystem service diversity were analyzed, with the α-multifunctionality index compared across major land cover types. The cumulative multifunctionality index helps prioritize broad-scale conservation efforts, whereas α-multifunctionality provides insights for diverse and targeted interventions

Quantifying key ecosystem services

The selection of key ecosystem services in the prairies was guided by the availability of data and informed by discussions with local stakeholders, including Ducks Unlimited Canada, Prairie Water project researchers, and ResNet collaborators in the prairies. We focused on pollination, carbon storage, soil erosion and sediment retention, water purification, habitat quality, and crop productivity. These services were all quantified spatially using InVEST models, with the exception of crop productivity, for which we developed a proxy-based index combining Normalized Difference Vegetation Index(NDVI) and the spatial density of crop types in the study area.

Pollination: Pollinator habitat sufficiency was assessed using the InVEST Crop Pollination model. The mean total pollinator abundance during spring and summer was used as a proxy for the pollination supply capacity of the landscape. Three key pollinator guilds in the prairies were considered: bumblebees, sweat bees, and mining bees, each with distinct seasonal activity patterns and foraging distances. These guilds play a critical role in ecosystem function by supplying pollination to floral resources, including croplands. A previous analysis by Pashanejad et al. (2023), which used a similar approach in ARIES, was instrumental in parameterizing the pollination model. The model coefficients were refined based on local literature reviews and expert opinions.

Carbon storage: We used the InVEST Carbon Storage and Sequestration model to identify the spatial distribution of areas with the highest carbon storage within the study area. This model is based on the carbon cycle and accounts for four distinct carbon pools—aboveground biomass, belowground biomass, dead organic matter, and soil carbon. It estimates total carbon storage at the pixel level using land cover data. For this study, we adopted the model parameters and coefficients from a previous analysis by Pashanejad et al. (2024), conducted on a smaller scale in central Alberta. Leveraging these validated parameters, including land cover-specific coefficients derived from both global and national datasets, we applied the model to the entire Canadian prairies. Specifically, carbon pool values for aboveground and belowground biomass were sourced from a global dataset (Spawn and Gibbs 2020), while soil carbon and dead organic matter values were informed by a national dataset produced by WWF-Canada (Sothe et al. 2022).

Soil erosion control (Sediment Retention): Similar to pollination and carbon storage, we used the InVEST Sediment Delivery Ratio (SDR) model, incorporating previous parameterization specifically tailored for the prairies (Pashanejad et al. 2024). The SDR model applies the Revised Universal Soil Loss Equation (RUSLE), which factors in climate, soil texture, topography, and land cover, alongside a connectivity index that accounts for the upslope and downslope characteristics of each pixel (Chaplin-Kramer et al. 2022). The model provides two primary indicators of sediment retention services: Avoided Erosion and Avoided Export. Avoided Erosion evaluates the effectiveness of vegetation in minimizing soil erosion at any given location, offering valuable insights for soil conservation efforts, particularly in agricultural regions where preserving topsoil is critical for soil fertility and food production (Guerra et al. 2022). Avoided Export, on the other hand, measures the reduction in sediment flow into water bodies due to vegetative cover, thereby supporting water quality regulation and ecological health (Project 2023). In this research, we selected avoided erosion, which serves as a proxy for the capacity of the landscape to provide soil erosion regulation services. A map of both SDR outputs are available in appendix X and X.

Nutrient retention: To quantify nutrient retention, we used the Nutrient Delivery Ratio (NDR) model of InVEST, focusing on nitrogen and phosphorus. The NDR model incorporates factors such as fertilizer application, precipitation, topography, and the retention capacity of vegetation. This model has been applied at various scales, including global contexts (Chaplin-Kramer et al. 2019, 2022). Since the model does not directly quantify nutrient retention as an ecosystem service, we calculated a relative efficiency of nitrogen retention at the landscape scale, as defined by the following equation:

$$NRE(p) = \frac{L_n(p) - E_n(p)}{L_n(p)}$$

Where: $L_n(p)$: The modified load of nutrient at pixel p, derived from modified output, representing the estimated initial nutrient load accounting for local runoff potential.

$E_n(p)$: The total nutrient export from pixel p, representing the amount of nutrient transported to water bodies.

$NRE(p)$ represents the efficiency of nutrient at pixel p, with values ranging between 0 and 1. A value of 1 indicates that all nutrients are retained within the pixel, showing maximum efficiency in nutrient retention and minimal contribution to downstream nutrient pollution. Conversely, a value of zero indicates all nutrients are exported from the pixel, contributing entirely to downstream nutrient loads and potential water quality degradation.

To tailor the model parameters for the prairie context, we conducted a comprehensive literature review of government guidelines and local studies on fertilizer application for different crop types grown in prairie farmlands. For crop-specific nitrogen application rates, we developed an approach based on insights from previous national nitrogen budget studies (Karimi et al. 2020).

Crop productivity: To quantify crop productivity, we developed a proxy-based index combining the Normalized Difference Vegetation Index (NDVI) and the spatial density of major crop types in the Canadian prairies. Using Google Earth Engine (GEE), we derived the MODIS product MOD13Q1, which provides 16-day composite NDVI values. The imagery collection was filtered for the period spanning June 1 to September 1, 2020, aligning with the peak growth season in the study region. To focus specifically on agricultural productivity, we utilized the AAFC Annual Crop Inventory within GEE to mask out non-agricultural areas, ensuring that only cropland vegetation contributed to the NDVI calculation. Subsequently, crop productivity was calculated by integrating mean NDVI values with spatial density data for annual crops. Spatial density values are raster-based numerical indicators of the proportion of each pixel's area likely to be occupied by annual crops, calculated from an analysis of the 2009–2021 AAFC Annual Crop Inventory. Pixels with higher spatial density values represent areas with a higher likelihood of annual crop cultivation . The methods for determining productivity scores involved adjusting NDVI values to exclude negative values indicative of non-vegetated areas and multiplying the adjusted mean NDVI values by the normalized spatial density of crops for each pixel. The formula for calculating the productivity score (PS) of each pixel is expressed as follows:

$$PS_i = NDVI_{adjusted,i} \times Spatial\ Density_i$$

Where:

$NDVI_{adjusted,i}$ is the adjusted mean NDVI value for pixel i, ensuring all values used in productivity calculations are positive.

$Spatial\ Density_i$ is the normalized spatial density of crops for pixel i. The crop productivity score (PS) ranges between 0 and 1, where higher values indicate areas with both high vegetation health as reflected by NDVI and a high likelihood of crop cultivation.

Habitat Quality: We used the Habitat Quality model from InVEST (Sharp et al. 2014), to indirectly indicate landscape potential to support biodiversity and, in turn, maintain ecosystem function. The model evaluates habitat quality based on land cover and land use data, incorporating factors such as the suitability of different land covers for biodiversity, the impact of various anthropogenic threats, and the sensitivity of each land cover or land use type to these threats (Terrado et al. 2016). In the prairies, grasslands, wetlands, and prairie potholes provide essential habitats for a wide variety of species, including pollinators, plains bison, swift fox, burrowing owls, and various waterfowl species that support multiple ecosystem functions. We developed a generalized habitat quality model rather than focusing on specific species, providing a broad overview of landscape suitability while accounting for significant threats to these habitats. The model parameters were informed by similar studies in the prairies, such as Akbari et al. (2021); and Shaffer et al. (2019), as well as government reports. For example we used Wildlife Habitat Capacity Index for agricultural lands that is developed and calculated at Soil Landscapes of Canada(SLC) scale as part of the Canadian Environmental Sustainability Indicators (Environment and Climate Change Canada 2024b). Key threats included in the model were agricultural expansion, road and railway construction, urban development, energy infrastructure, and major industries with significant CO2 emissions, as identified in the Canadian Environmental Sustainability Indicators. Table 1 below provides a full list of threats we considered in the model. InVEST HQ model applies a distance decay function to represent how the intensity of each threat diminishes with distance. The model also considers habitat sensitivity, recognizing that natural habitats are generally more vulnerable to disturbances, while croplands and other modified landscapes have already undergone significant changes from their original state. For example, wetlands and native grasslands, which provide critical habitat for biodiversity, have higher sensitivity scores, meaning they are more susceptible to degradation from nearby disturbances.

Table 3. Anthropogenic threats considered in the InVEST Habitat Quality model for the Canadian prairies.

Threat	Description
Crop Expansion	Agricultural intensification replacing natural habitat
Pastureland Expansion	Conversion of native prairie to managed grazing lands
Urban Development	Expansion of cities, towns, and rural settlements
Major Roads	High-traffic roads increasing fragmentation
Secondary Roads	Low-traffic roads affecting local habitat connectivity
Railways	Rail infrastructure impacting species movement
Oil Extraction (Active)	Ongoing oil and gas extraction operations
Oil Extraction (Inactive)	Abandoned extraction sites
Power Plants	Energy production sites contributing to pollution & habitat disturbance
Emissions from Major Industrial Sources	Industrial CO_2 emissions contributing to air pollution

ES multifunctionality indices

We developed two ES-based indices to explore the multifunctionality of service provisioning at the landscape scale. The first approach is the aggregated level of all ES delivery at each location (e.g., pixel or unit) and is the cumulative ES provisioning index that accounts for the total provisioning of multiple ES. The cumulative index was calculated as the sum of the normalized ES rasters including pollination, habitat quality, carbon storage, nutrient retention, soil erosion control and crop productivity.

$$M(x) = \sum_{i=1}^{N} ES_i(x)$$

where $M(x)$ is the multifunctionality index at location x, $ES_i(x)$ is the normalized values of ecosystem service i at location x. N is the total number of ecosystem services considered.

The α-multifunctionality on the other hand, accounts for the service evenness and diversity of multiple ES that comes from the single ES provisioning units such as pixel or at any aggregated unit. It reflects how balanced or heterogenous the contribution of different ES are at a given pixel or unit. We followed the method applied by Simion et al. (2023), using the Gini-Simpson diversity index for the selected ES in the study area. The ES diversity index expressed as:

$$\alpha = 1 - \sum_{i=1}^{N} p_i^2$$

where α is the α-multifunctionality at a given location, N is the total number of ES considered and P_i is the proportion of the supply of ES i relative to the total ES supply at the location. In this index high values indicate high diversity meaning many ES are contributing evenly and low values indicate low diversity (i.e., one or few ES dominate relatively to the all other ES considered). While some areas may excel in delivering one or two key services, landscapes that support a more even mix of services are generally more resilient to stress and better suited for sustaining multiple objectives such as food production, biodiversity, and climate adaptation.

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