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Prioritizing ecological restoration of converted lands in Canada by spatially integrating organic carbon storage and biodiversity benefits

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Abstract

Ecosystem restoration is a fundamental way of delivering nature-based solutions to improve resilience in a changing climate and sustain biodiversity. Spatial analyses to identify where ecosystem restoration would yield targeted environmental benefits are critical to inform, and coordinate restoration initiatives at multiple scales to achieve national commitments and global goals. Here, we provide an optimization analysis for restoration potential of converted terrestrial ecosystems in Canada by integrating carbon storage and biodiversity benefits as key considerations. Our results show that converted landscapes are prevalent in southern anthropic regions of Canada, with the greatest potential for biodiversity benefits through forest and grassland restoration. At national scales, carbon density (tonnes C/km^2) and total carbon storage (tonnes C) potential were greatest for wetland and forest restoration, respectively. When biodiversity and carbon were both included in an optimization framework, consistent priorities across all three restoration targets (50,000; 100,000; and 150,000 km^2) comprised forest restoration in the St. Lawrence and Lake Erie Lowlands, with the Lake Manitoba Plains, Interlake Plains, and Manitoulin-Lake Simcoe ecoregions also frequently identified. Our analysis will help decision-makers identify where restoration of converted lands may support considerable gains in simultaneously achieving climate and biodiversity goals in Canada.

KEYWORDS
biodiversity, Canada, carbon storage, ecosystem restoration, human footprint, landcover, machine learning, nature-based solutions, spatial prioritization

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1 | INTRODUCTION

The interconnectedness of the environmental crises of climate change and biodiversity loss underscores the need for addressing these issues simultaneously (IPCC, 2019; Turney et al., 2020). Accordingly, the potential of nature-based solutions (NbS)—approaches that use nature to address environmental emergencies (Seddon et al., 2021)—has recently gained popularity, as they can simultaneously support multiple United Nations Sustainable Development Goals (Gómez Martín et al., 2020). NbS include protection, restoration, and sustainable management of natural and/or modified ecosystems (Cohen-Shacham et al., 2019), to safeguard and sequester CO_2, while delivering benefits for biodiversity and human wellbeing (Seddon et al., 2021). Critically, they must be designed and implemented with active support and Indigenous consent if they are to be effective (Townsend et al., 2020). The need for rights-driven and integrated policies was evident in recent United Nations climate and biodiversity conferences, where Indigenous rights and responsibilities, as well as nature's indispensable role in achieving environmental targets were evident in the final texts. For instance, the Kunming-Montreal Global biodiversity framework includes targets (e.g., Target 2) to restore ecosystem functions and services to enhance biodiversity and regulate climate (CBD, 2022).

Ecosystem restoration is fundamental to conserving biodiversity and recovering ecosystem processes (IPBES, 2019). To underscore its potential as a conservation tool, the United Nations General Assembly has proclaimed the current decade (2021–2030) as the Decade on Ecosystem Restoration. Similarly, the Government of Canada has formally committed to ecological restoration in its 2021 Nationally Determined Contribution submitted to the United Nations Framework on Climate Change (Government of Canada, 2021a). The federal government has also committed to halt and reverse species loss in its mandate letter to the Minister of Environment and Climate Change (Government of Canada, 2021b) and plant two billion trees over 10 years (NRCan, 2020)—commitments that recognize restoration as a necessary pathway for conservation.

Given global goals and national commitments to restoration, systematic conservation planning tools can provide decision-makers with the necessary information to strategically prioritize areas for restoration that would provide maximum biodiversity and carbon storage benefits. In contrast to prioritization analyses for protected areas (Coristine et al., 2019; WWF-Canada, 2022), an evidence-based framework to guide restoration has yet to be adopted for Canada—though some exist at local levels (PC, 2008; TRCA, 2015) and have been proposed for specific ecosystems (Mansuy et al., 2020).

Here, we explore optimization methods to identify potential areas for restoration of converted terrestrial ecosystems in Canada. Given the existing ecological diversity in Canada and its importance for resilience into the future, we consider physical restoration potential across all terrestrial ecosystem types nationally. This decision is deliberately in contrast to the current overemphasis on tree-based restoration (Seddon et al., 2021), which does not acknowledge the potential climate mitigation and biodiversity gains in non-forested ecosystems. Moreover, we provide four novel data layers that are specific to Canada:

i. converted lands that would benefit from restoration;
ii. potential carbon storage of converted lands that would benefit from restoration;
iii. potential biodiversity benefits of converted lands that would benefit from restoration; and
iv. spatial prioritization of converted lands that would benefit from restoration.

2 | METHODS

The analysis focused on prioritizing ecological restoration of converted terrestrial landscapes in Canada—a country over 9.98×10^6 km^2 in size. As Canada stores approximately one-fifth of the world's soil carbon in its natural ecosystems (Sothe et al., 2022) and is home to over 800 species designated as at risk (including populations and subspecies) (ECCC, 2022), integration of both biodiversity and organic carbon storage benefits in conservation planning is critical. To spatially prioritize restoration initiatives across Canada, we first identified converted lands that would benefit from restoration, then integrated key considerations of potential carbon storage and biodiversity benefits for these areas, before evaluating the overlap and optimization of these elements (Figure S1).

2.1 | Assessment of converted lands that would benefit from restoration

We used current landcover to identify "converted lands that would benefit from restoration" as those that have been converted to human-dominated landcover classes, including croplands and urban areas, in addition to human-dominated portions of barren lands, grassland, and shrubland (Table S1)—an approach in line with Cook-Patton et al. (2021) that focuses on recovering converted ecosystems. While restoration could and should be endeavored for degraded ecosystems, including forests and wetlands, spatially explicit, nationwide degradation data for multiple ecosystem types is not currently available, and thus, the scope of our analysis exclusively considered the restoration of converted lands.

Landcover data were obtained from the Annual Canadian Crop Inventory (AAFC, 2019). Given that the spatial coverage of the data was limited to the agricultural extent in southern Canada, the North American Land Change Monitoring System (CEC, 2015) was used as a supplement—extending the spatial coverage of the data to encompass northerly areas. The data were reclassified into nine landcover categories that were consistently applied across datasets (Table S2). Using Canadian human footprint data (Hirsh-Pearson et al., 2021) and disturbance data (Guindon et al., 2017), barren, grassland and shrubland landcover classes were further refined into "near-natural" and human-dominated states based on where they coincide with detectable human impacts (Table S1). Global human footprint (Venter et al., 2016) was used to fill in gaps in national data (specifically small gaps around large water bodies).

Since some forms of landcover modification are not consistently detected at the spatial resolution of 30 m, we supplemented the proportional estimates of all landcover classes using vector data representing linear features, which were treated as land conversion. We used the best available data describing national coverage of roads, single track trails, and seismic lines (Poley et al., 2021) and applied buffer distances corresponding to average widths (Leu et al., 2008; Theobald, 2013) to calculate their areal extents. These features were then dissolved and converted to grids with fractional proportions (using Baston, 2021). The fractional coverage values were then integrated with those generated from landcover data using a max filter. This had the effect of increasing estimated human-dominated landcover in locations where remotely sensed landcover products alone may fail to capture the impacts of human linear features that result in land conversion.

Following reclassification, landcover was transformed into fractional data at a 250 m pixel resolution, with values representing the proportion of the total cell area defined by a given landcover class, which resulted in one data layer per landcover class. The conversion was done using *reduceResolution* in Google Earth Engine; when applied with the mean reducer, for each landcover it provides the portion of the 250 m pixel covered by a given landcover class at the original 30 m resolution. The analysis hinges on the assumption that pixels would be restored to near-natural conditions, and thus urban areas (representing 11.68% of converted lands that would benefit from restoration) were removed.

2.2 | Key considerations

2.2.1 | Assessment of landcover and carbon storage that would have existed in the absence of conversion to human-dominated landcover classes

To investigate the potential of restored lands to contribute to climate change mitigation and biodiversity recovery, we first required an assessment of landcover and associated carbon storage that would exist in the absence of land conversion to human-dominated landcover classes. We applied the multivariate nonparametric *k* nearest neighbors (*k*NN) method to impute attributes of both landcover and carbon density for each pixel containing converted lands (Figure S2). This modeling approach broadly relies upon drawing inference from remaining areas with near-natural landcover to estimate the attributes (i.e., landcover and carbon storage) of human-dominated areas with similar environmental characteristics. The *k*NN algorithm was selected due to its ability to simultaneously predict multiple attributes (i.e., multivariate regression) while maintaining within-attribute relationships, in addition to its effective application for this type of analysis (Beaudoin et al., 2014; Fu et al., 2019; McRoberts, 2012) (see Supplemental Materials for detailed methods).

2.2.2 | Potential carbon storage of converted lands that would benefit from restoration

Once carbon storage capacity values were imputed for lands that would benefit from restoration via the *k*NN model, these values were then used to derive the estimated change in carbon storage that would occur following successful restoration, as per Strassburg et al. (2020). To this end, we first converted the carbon density values (tonnes C/km^2) to total carbon storage values (tonnes C) within each cell by multiplying the carbon density value by the area of human-dominated land within each cell. We then subtracted the amount of carbon estimated to currently exist on these lands based on the corresponding human landcover carbon coefficients (Table S5) to arrive at delta carbon values. Human landcover carbon coefficients were derived as the median aboveground and belowground carbon density estimates for locations with >70% cover associated with human land use or conversion (see Supplementary Material).

2.2.3 | Potential biodiversity benefits of converted lands that would benefit from restoration

To investigate the potential of restored lands to contribute to biodiversity benefits, we employed a modified Species Threat Abatement and Restoration (STAR$_R$) metric (Mair et al., 2021) for terrestrial and wetland species. The calculation of the STAR$_R$ metric was modified by restricting the scope to Canada and by retaining the lowest IUCN category (i.e., Least Concern) to showcase the value of conserving and preventing declines in biodiversity (see Supplementary Material for additional details), and to incorporate culturally important species—many of which are assessed as nonthreatened (Reyes-García et al., 2023).

$STAR_R$ incorporates species restorable area of habitat (using species ranges and habitat associations/ landcover preferences), status (e.g., critically endangered), and rarity into a single spatially explicit metric. Data for terrestrial species with ranges in Canada were retrieved from the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2021)—the most comprehensive dataset available at the time of publication. We filtered species by their presence, origin, status and habitat association (see Supplementary Material; Table S6). In total, 756 Canadian species with available range maps were included for analysis. Generally, the $STAR_R$ metric assesses the area of restorable habitat as a proportion of total existing area of habitat—weighted by status—within a spatial unit (i.e., 250 m^2 pixel). Existing habitat was evaluated using IUCN range data and current landcover, while restorable habitat incorporated IUCN range data and imputed natural landcover proportions from our *k*NN model (see Supplementary Material). The refined ranges were rasterized and harmonized with the imputed natural landcover proportions, as calculated via the *k*NN model. Outputs for all species were combined into a single data layer, representative of the potential biodiversity benefits of restoring converted lands, rather than the current location of species across Canada.

2.3 | Spatial prioritization of converted lands that would benefit from restoration

The three interim outputs (converted lands that would benefit from restoration and the potential carbon storage and biodiversity benefits within those areas) were integrated to produce a spatial prioritization product for Canada. Integration and optimization of data layers were conducted using the Restoration Opportunities Optimization Tool (ROOT; Figure S6)—a linear optimizer developed by the IUCN and Natural Capital Project (Beatty et al., 2018)—that has been applied to inform ecosystem service tradeoffs (e.g., Li et al., 2020; Villarreal-Rosas et al., 2022).

Primary analysis was done at a 250 m spatial resolution to match that of other inputs. However, for summarizing and visualizing results, we aggregated outputs to 100 km^2 hexbins. When run, ROOT produces multiple realizations (i.e., solutions), and therefore maps depict the frequency with which a hexbin was selected. Each realization attempts to optimally select hexbins which together maximize the total realized benefit as quantified by the input values (i.e., carbon and biodiversity benefits). For the purposes of our analysis, biodiversity and carbon benefits were weighted equally, and ROOT accounted for the spatial extent of restoration potential per pixel. ROOT was set to identify an optimal solution (using six realizations) for achieving three targets: 50,000; 100,000; and 150,000 km^2 of restoration across Canada. These targets represent 10, 20, and 30% of converted lands (and 0.5–1.5% of Canada's total land mass) that could benefit from restoration, aligning with and showcasing a path forward for Target 2 under the Kunming-Montreal Global biodiversity framework that specifies a 30% restoration goal by 2030, but also includes degraded lands (CBD, 2022).

In addition to ROOT, we included a complimentary bivariate map prioritizing the overlap of average biodiversity ($STAR_R/km^2$) and carbon density (tonnes C/km^2) potential. This approach differs in that a set target (e.g., 100,000 km^2) is not required, and it also retains information specific to each layer, showcasing the overlap of the two ecological considerations evaluated. Note that our quantification of potential benefits (i.e., net carbon storage and biodiversity benefits) lacks a temporal dimension, similar to other analyses of this kind (e.g., Strassburg et al., 2020).

3 | RESULTS

3.1 | Converted lands that would benefit from restoration

Our national map of converted lands that would benefit from ecosystem restoration are clustered in southern Canada, with the greatest spatial extent of disturbance in croplands of the prairies, southern Ontario and Quebec (Figure 1). Among converted lands (490,935.24 km^2), forest (33.8%) and grassland restoration (34.5%) represent the greatest opportunities for restoration, while restoration of lichen and barren represents <1.5% of the total restoration potential across Canada (Figure 2a). Spatially, the potential for grassland restoration is largely restricted to the Prairie ecozone (Figure S7). Alternatively, the potential for forest restoration in Canada is pervasive, ranging from coast to coast and is greatest in the Boreal Plains and Mixedwood Plains ecozones (Figure 2b; Table S7). There is opportunity for 75,482.64 km^2 of shrubland and 73,605.59 km^2 of wetland restoration nationally, with patterns evident in the Prairie ecozone (Figure S7). Converted lands that would benefit from restoration are predominantly composed of croplands (91.31%) (Figure S8).

3.2 | Potential carbon storage of converted lands that would benefit from restoration

The carbon storage potential of restoring converted lands in Canada can be evaluated by both carbon

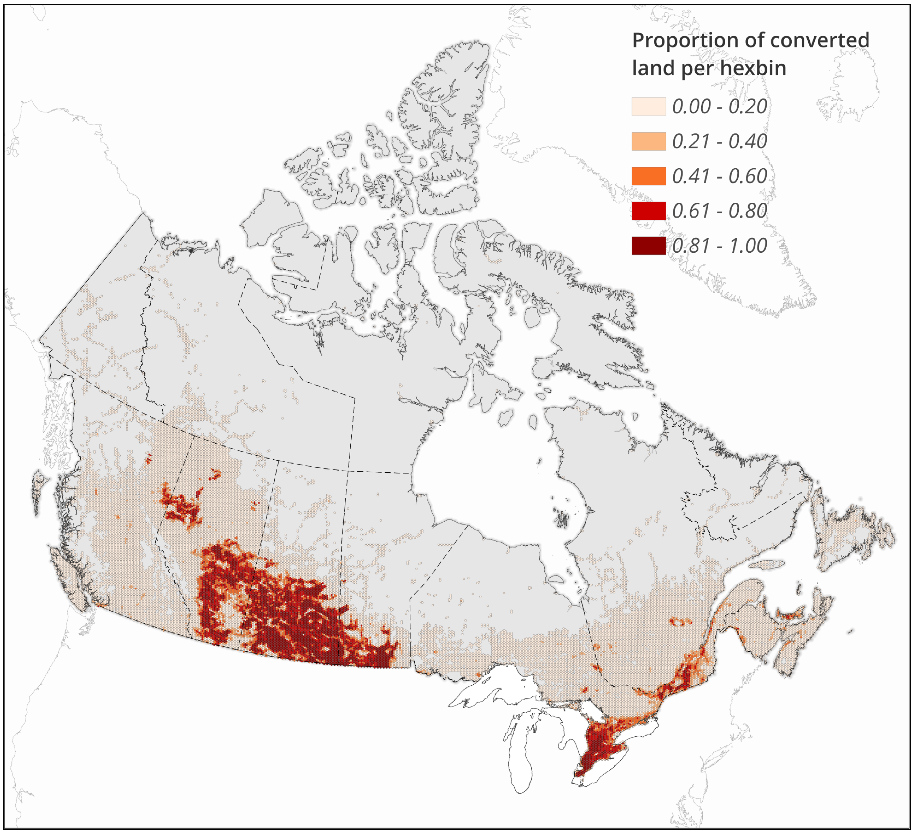

FIGURE 1 Converted lands in Canada that would benefit from restoration, at a 100 km^2 hexbin resolution. Color gradient depicts the proportional spatial extent of human disturbance per hexbin, ranging from 0 (least converted) to 1 (most converted).

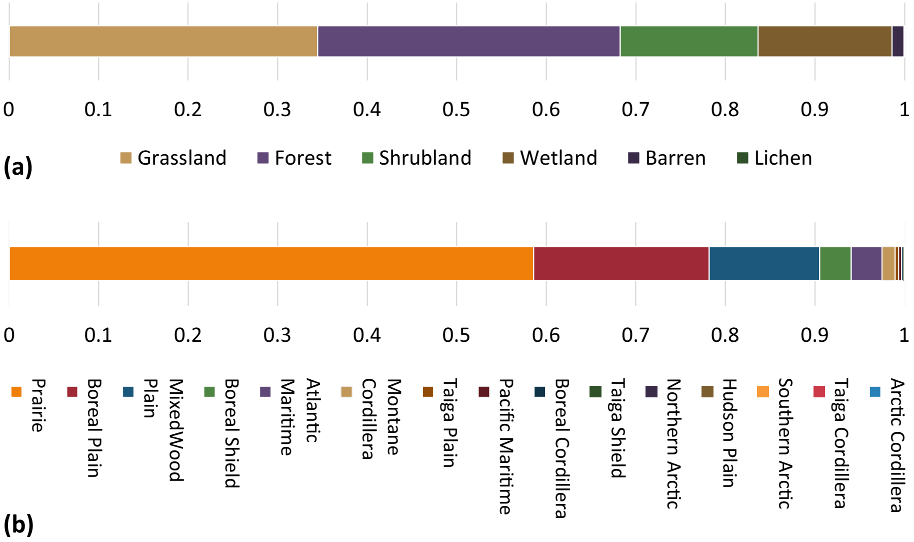

FIGURE 2 Proportional representation of (a) predicted landcover classes and (b) Canadian ecozones following ecosystem restoration of converted landscapes in Canada.

density (tonnes C/km^2) and total carbon storage (tonnes C). High carbon density values (tonnes C/km^2) are most evident in the periphery of areas identified for restoration in Canada (Figure 3a), spatially aligning with lands identified for forest and wetland restoration (Figure S7). Total carbon storage potential (tonnes C) follows an alternative pattern—aligning more closely with the map of restoration potential (Figure 3b). Net carbon density and total carbon storage potential are greatest in wetland and forest ecosystems, respectively (Figure S9).

3.3 | Potential biodiversity benefits of converted lands that would benefit from restoration

Biodiversity benefits exhibit a strong south to north gradient following high to low potential (Figure 4), regardless of including species assessed as Least Concern (Figure S11). Large average $\mathrm{STAR_R}$ metrics ($\mathrm{STAR_R}$/km^2) are clustered in southern Canada, particularly in the Prairies and Mixedwood Plains. These ecozones are also prominent when assessing total $\mathrm{STAR_R}$ values,

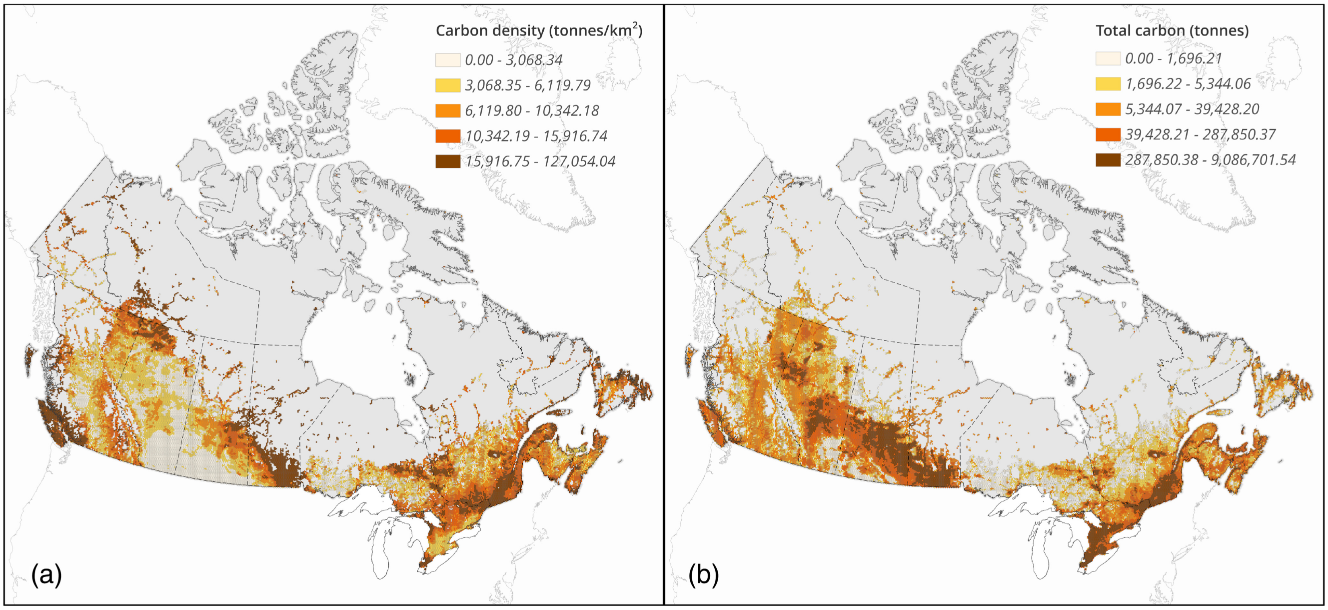

FIGURE 3 (a) Carbon density (tonnes C/km^2) and (b) total carbon storage (tonnes C) potential of restoring converted lands in Canada, at a 100 km^2 hexbin resolution. Color gradient is visualized using quantiles.

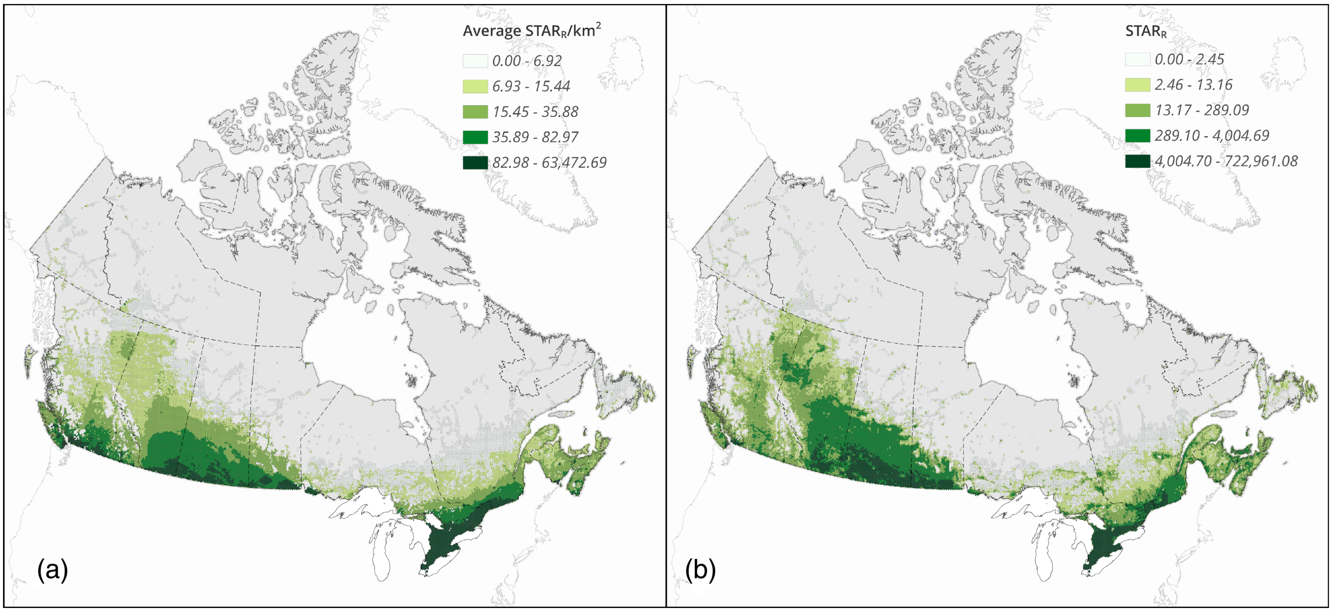

FIGURE 4 (a) Average (STAR$_R$/km^2) and (b) total (STAR$_R$) STAR restoration scores for species in Canada, at a 100 km^2 hexbin resolution. Color gradient is visualized using quantiles.

which are skewed toward the spatial extent of restoration potential (Figure 4b). Species of Least Concern comprise the largest group included within the analysis (91.5%; Figure S10a), though they are given a lesser weighting to recognize and prioritize species that are more prominently threatened with extinction (see Supplementary Material). Of the 756 species included in the analysis, birds are the best represented (52.9%), followed by mammals (20.4%) (Figure S10b). Conversely, despite considerable numbers of plant and arthropod species found in Canada, comparatively few are included within the terrestrial restoration analysis due to a lack of accompanying spatial data.

3.4 | Spatial prioritization of converted lands that would benefit from restoration

Our prioritization maps illustrate the spatial relationship between biodiversity and carbon benefits of restoring converted lands in Canada (Figure 5). While the linear optimization approach (i.e., ROOT) is more complex and process-oriented (providing the optimal areas where defined restoration targets would generate the highest benefits with the fewest trade-offs), the bivariate map is complementary in that it retains areas that are important for either biodiversity or carbon and does not specify an area-based target. The two spatial prioritization approaches are normalized by the area of converted lands and are largely aligned, boasting a 70% overlap of priority restoration areas (estimated using the 100,000 km^2 target; Figure 5). Despite defining area-based targets, each realization of ROOT produces a new set of pixels via the optimization process. Consequently, the areas that are the most optimal (and thus of highest priority) for restoration equate to 9,500; 26,000; and 39,000 km^2 (corresponding to targets of 50,000; 100,000; and 150,000 km^2, respectively)—averaging approximately one quarter of the initial target—and are best suited to forest restoration of croplands. The potential carbon benefit ranges from

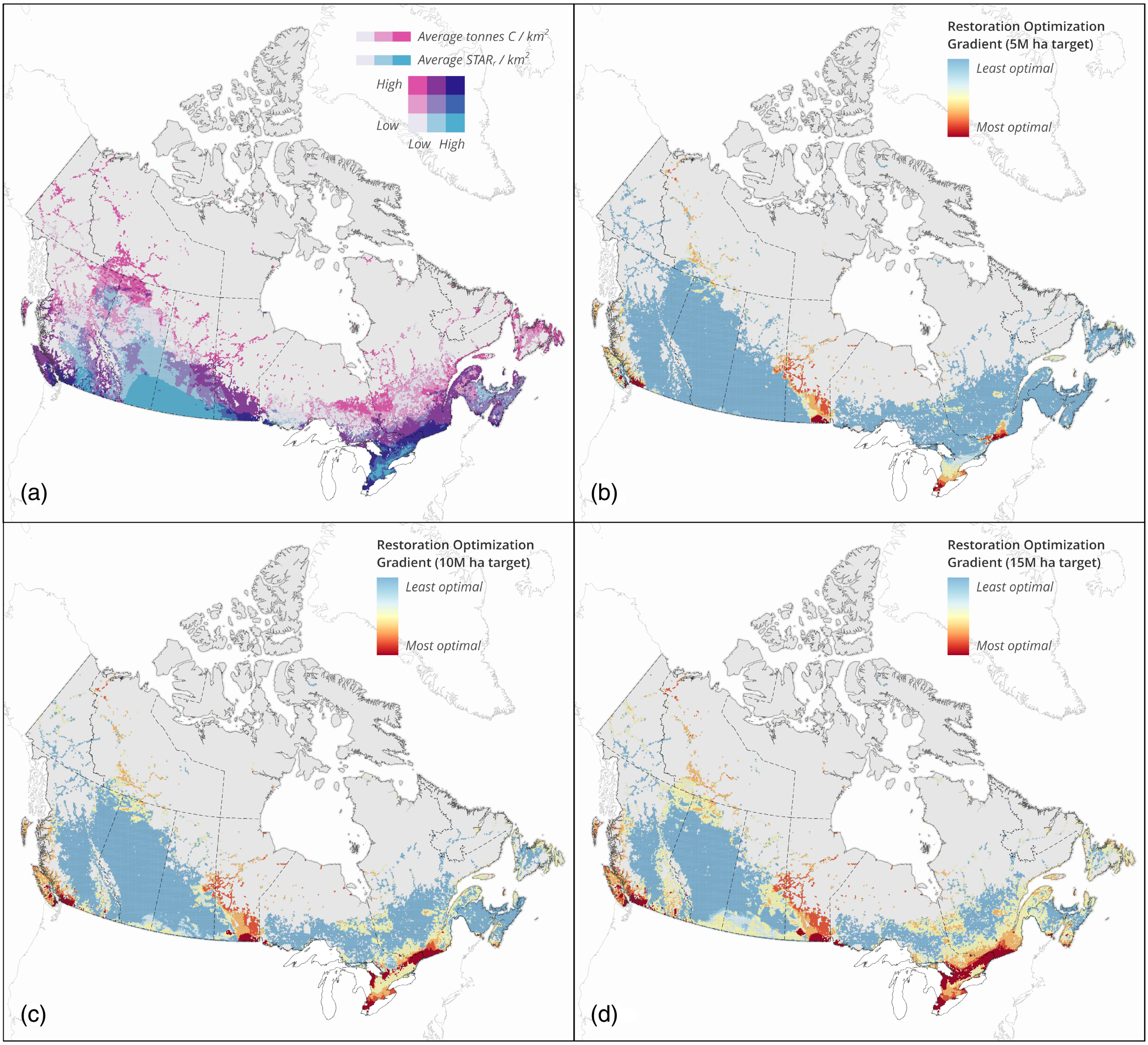

FIGURE 5 Spatial prioritization of converted lands in Canada that would benefit from ecological restoration, using (a) a simple overlay of carbon and biodiversity benefits, classified by tertiles, and a linear optimization approach (using Restoration Opportunities Optimization Tool [ROOT]) that approximates the optimal solution for maximizing both the carbon and biodiversity benefits of restoration using a (b) 50,000 km^2; (c) 100,000 km^2; and (d) 150,000 km^2 restoration target. Color gradients depict (a) average biodiversity (STAR$_R$/km^2) and carbon density (tonnes C/km^2) benefits for converted lands, and (b–d) the frequency in which a pixel was selected to achieve an optimal solution.

295.58 to 836.20Mt C if all of the most optimal areas (i.e., hexbins selected six times in ROOT) are restored. Restoration in the Mixedwood Plains ecozone generated the highest biodiversity and carbon benefits and is thus most optimal for restoration (i.e., hexbins selected six times by ROOT), followed by restoration in the Prairie ecozone. Restoration in the Boreal Plains, Boreal Shield, Pacific Maritime, and Atlantic Maritime ecozones are also noteworthy, but their relative priority differs depending on the area-based target adopted (Figures 6 and S12). At a finer scale, consistent priorities (i.e., hexbins selected four to six times by ROOT) across all three restoration targets comprise forest restoration in the St. Lawrence and Lake Erie Lowlands, with the Lake Manitoba Plains, Interlake Plains and Manitoulin-Lake Simcoe ecoregions also frequently identified. While grassland restoration in

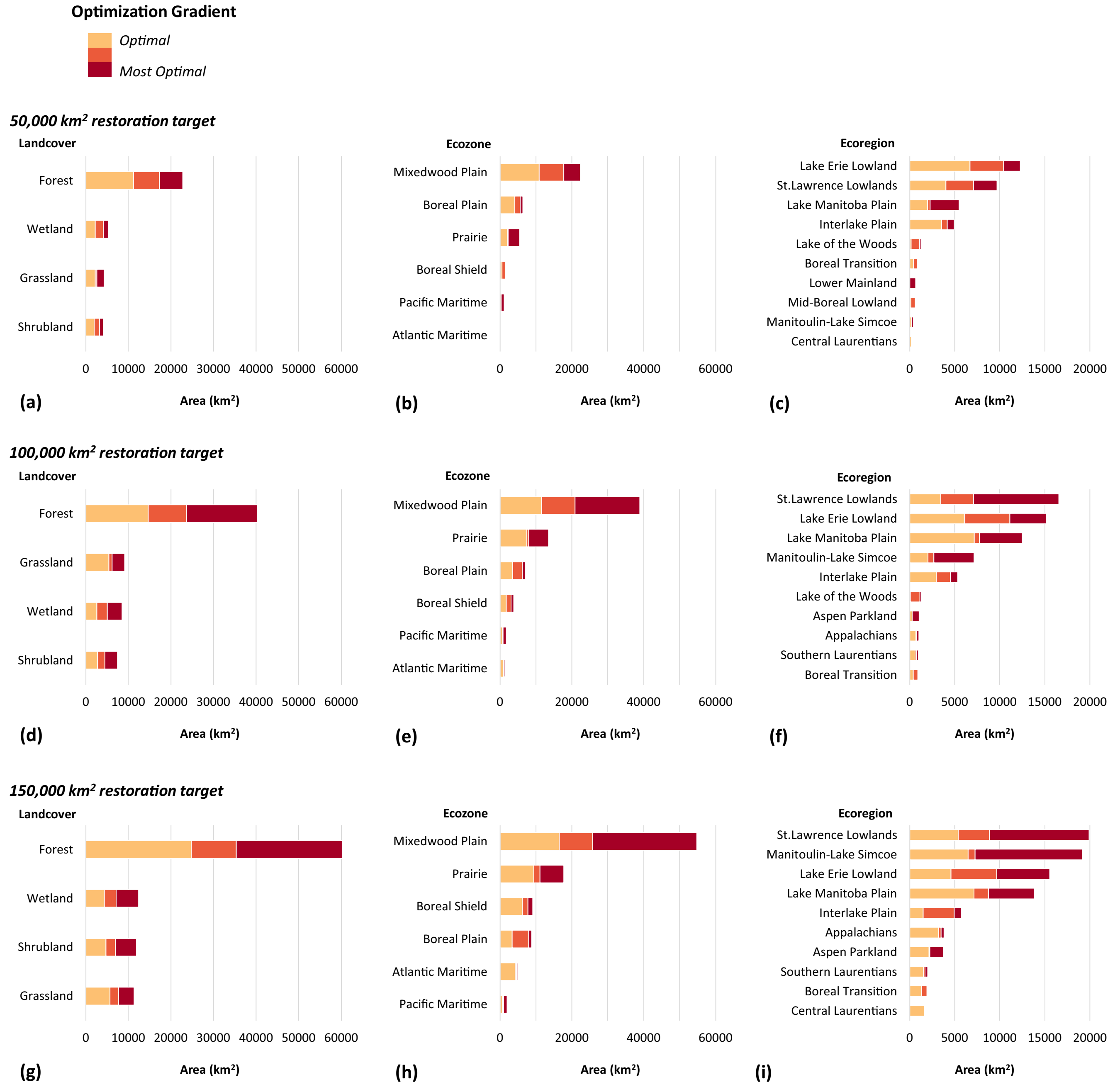

FIGURE 6 Proportional representation of predicted landcover classes ecozones and ecoregions for the 50,000 km^2 restoration target (a–c); (100,000 km^2 restoration target (d–f); and 150,000 km^2 ha restoration target (g–i) within the linear optimization approach (using Restoration Opportunities Optimization Tool [ROOT]), following ecosystem restoration of converted landscapes. Colors depict the frequency in which a pixel was selected to achieve the optimal solution. Only landcover classes, ecozones, and ecoregions with highest restoration potential are showcased.

the Prairie ecozone has the greatest total area of converted lands that would benefit from restoration (Figure 2), it also contains the largest area of pixels that are least optimal once biodiversity and carbon benefits are integrated via ROOT (Figure S13).

4 | DISCUSSION

We demonstrate how combining biophysical spatial data can facilitate the identification and optimization of areas for restoration across Canada—which will support the allocation of resources to maximize conservation benefits and reduce costs (Strassburg et al., 2019). In addition, restoration initiatives must respect social safeguards, take into consideration the knowledge and needs of Indigenous Peoples and local communities to optimize success, and consider the local contexts in which restoration will take place (Gann et al., 2019; Seddon et al., 2021; Townsend et al., 2020). Consequently, the analysis presented here serves as one component of a multifaceted approach needed for restoration—one that includes a local and more holistic conservation planning process.

Our analysis supports prioritization at a national scale, and does not reflect sociopolitical or territorial boundaries, where implementation may be more applicable. Many areas identified as restoration priorities are located within Indigenous territories, reflecting a history of externally imposed degradation. Accordingly, restoration efforts should uphold the United Declaration on the Rights of Indigenous Peoples, including the principle of Free, Prior and Informed Consent. In practice, initiatives should guarantee Indigenous governance, knowledge and self-determination—aligning with recommendations from the Indigenous Circle of Experts (ICE, 2018).

4.1 | Spatial prioritization of restoring converted lands in Canada

4.1.1 | Restoration potential of converted lands

Converted landscapes—covering more than 5% of Canada (AAFC, 2019; CEC, 2015)—are prevalent in the south, aligning with human footprint, where roads, croplands and population density are highly concentrated geographically. Areas with high human footprint cover approximately 6% of the country and are representative of areas with 12 compounding pressures to biodiversity, based on current data (Hirsh-Pearson et al., 2021). Within our analysis, converted landscapes that would benefit from ecological restoration include croplands in the Prairies and Boreal and Mixedwood Plains ecozones—ecozones dominated by high human footprint (Hirsh-Pearson et al., 2021). The optimization approach employed in our analysis adopts three targets of restoring 10, 20, and 30% of converted lands that could benefit from restoration in Canada (representing 0.5–1.5% of Canada's total land mass). Given these relatively small targets, the areas highlighted as spatial priorities for restoration are disproportionately vital for achieving multiple environmental targets.

4.1.2 | Carbon potential

Using average values from data products depicting spatially explicit carbon stocks in Canada (Poggio et al., 2021; Sothe et al., 2022; Soto-Navarro et al., 2020), we produced a novel resource depicting the difference in carbon stock following ecosystem restoration—representing net carbon potential. By assessing the carbon potential of restored lands at a national scale, we can gain a deeper understanding of the types of restoration actions needed, and where to implement them. Net carbon density and total carbon storage potential was greatest for wetland and forest restoration, respectively. Soil organic carbon contributed the greatest carbon sequestration potential regardless of landcover class, while the net carbon density and total carbon storage potential of plant biomass was highest for forests. Previous research has also identified the forest sector as having the largest 2050 restoration mitigation potential in Canada (Drever et al., 2021), and thus the current emphasis of tree planting in Canada may be warranted. Accordingly, these results are relevant to Canada's recent pledge to the Bonn Challenge (NRCan, 2022), and its target of planting two billion trees by 2030 (NRCan, 2020). Yet, there are many caveats associated with successful and long-lasting forest restoration, including the need for long-term stewardship, appropriate siting to ensure resiliency and carbon storage, among others (Seddon et al., 2021). Thus, overreliance and a sole focus on tree planting should be mitigated by applying a more holistic approach that restores, connects, and safeguards multiple ecosystems and functions.

These results also emphasize the importance of preserving and restoring Canada's wetlands. High carbon values for wetlands are driven by peatlands, which store nearly one-third of country's soil carbon despite covering only 12% of Canada and contain a carbon density roughly three times that of open wetlands (Sothe et al., 2022). Notably, our analysis did not incorporate a temporal dimension for carbon storage potential, and it is likely that the timeframe for carbon recovery exceeds the necessary timescale to keep warming below 1.5–2°C

(Cook-Patton et al., 2021; Goldstein et al., 2020). This is especially true for inland wetlands, where it can take centuries to achieve a net cooling effect due to methane release post-restoration (Taillardat et al., 2020), and where restored carbon rarely achieves the level of natural systems (Xu et al., 2019). Similarly, the loss and attempted restoration of irrecoverable carbon—encompassing high-carbon, slow-recovery ecosystems such as peatlands, marshes and old-growth forests (Goldstein et al., 2020; Noon et al., 2022)—reinforces the need to prioritize proactive protection (Goldstein et al., 2020) over restoration. Furthermore, the restoration of freshwater mineral wetlands and peatlands are comparatively expensive NbCS pathways in Canada (Drever et al., 2021). Thus, while prioritization exercises are useful for maximizing multiple benefits, socioeconomic and ecological tradeoffs are pervasive and must be thoughtfully considered.

4.1.3 | Biodiversity potential

While many other "biodiversity layers" depict similar spatial patterns in Canada, they are often limited to vertebrates (e.g., WWF-Canada, 2022) and/or species at risk (e.g., Coristine et al., 2019). The modified STAR_R product developed here also incorporates plants and animals, including those assessed as Least Concern, to reflect biodiversity more broadly. Nonetheless, the STAR_R metric assigns greater weight to threatened species, as well as endemics and those with small Canadian distributions among the species included. Consequently, STAR_R hotspots are particularly prevalent in the Prairies and Mixedwood Plains—areas delineated by intensive land-use from agriculture and development that are consequently occupied by numerous species at risk (Coristine et al., 2019; Coristine & Kerr, 2011). These spatial patterns are particularly evident for birds (eBird Canada, 2018) and other species occupying the northern periphery of their range (Gibson et al., 2009; Lesbarrères et al., 2014).

4.1.4 | Spatial prioritization

Canada contains over 7M km^2 of the world's remaining wilderness (Watson et al., 2018) and conserving the comparative intactness of these ecosystems is crucial for contributing to the persistence of global biodiversity (Allan et al., 2022; Di Marco et al., 2019) and climate regulation. Canada thus holds a disproportionate global responsibility—and leadership opportunity—to protect and manage its large territory to prevent further degradation of ecological functioning. Nevertheless, Canada's wilderness areas are juxtaposed against areas under immense anthropogenic pressure (Hirsh-Pearson et al., 2021), where ecological restoration will be fundamental for remediating negative impacts. Serving as the final step in the NbCS hierarchy (Cook-Patton et al., 2021), ecological restoration is anticipated to yield the lowest annual climate change mitigation potential in the short term in comparison to protection and sustainable management in Canada (Drever et al., 2021). However, the value of ecological restoration increases over time—with restoration of forest cover resulting in >200-fold increase in annual mitigation potential by 2050 relative to 2030 (Drever et al., 2021). Recognition of the NbCS hierarchy (protect, manage, then restore) and the disproportionate long-term benefits of ecological restoration is important for contextualizing restoration in Canada, and for ensuring a more appropriate allocation of resources within this hierarchy (Cook-Patton et al., 2021). Though ecological restoration of converted lands would support progress on multiple environmental goals, the contributions of improvements to carbon and biodiversity within working lands (i.e., sustainable management of converted lands where "full restoration" is not undertaken) is also a massive opportunity that is anticipated to yield the greatest climate mitigation potential by 2030 in Canada (Drever et al., 2021), and thus warrants consideration to achieve the scale of impact necessary.

While quantitative targets and prioritization exercises exist for protected and conserved areas, there is currently no equivalent for ecological restoration in Canada—hence, the application of two spatial prioritization approaches. We ran our analysis using 50,000; 100,000; and 150,000 km^2 restoration targets, integrating both biodiversity and carbon as key considerations for prioritization. Areas for ecological restoration are present in every province and territory, regardless of the prioritization approach endeavored.

Agricultural expansion, particularly the conversion of forests to croplands, remains the main driver of land conversion in Canada (ECCC, 2021) and globally (Winkler et al., 2021), and thus forest restoration is frequently identified within our analysis. In particular, forest restoration in the Mixedwood Plains ecozone generated the highest biodiversity and carbon benefits of converted lands, regardless of the restoration target specified. At a finer resolution, consistent priorities across all three restoration targets comprised the Lake Erie and St. Lawrence Lowlands. These "crisis" ecoregions have previously been identified among the most significant and threatened places for biodiversity conservation, boasting some of the highest rates of land conversion in Canada (Kraus & Hebb, 2020). The Lake Manitoba Plains, Interlake Plains and Manitoulin-Lake Simcoe ecoregions were also frequently identified as restoration priorities. Notably, priority areas are spatially congruent with the global reactive biodiversity and carbon density bivariate maps produced by Soto-Navarro et al. (2020). Consequently, the priority regions highlighted in our analysis coincide with global priorities for restoration—representing areas of high threat and comparative value for biodiversity and climate change.

To date, studies evaluating forest restoration have received the greatest attention relative to other ecosystems (Guan et al., 2018), suggesting that there may be more resources to guide forest restoration in Canada—a priority landcover class according to our analysis. Moreover, restoration initiatives do not necessarily need to be supplementary to current conservation priorities; rather, an integrated approach to conservation is useful for achieving multiple policy objectives more efficiently.

Importantly, despite the need to address anthropogenic impacts through ecological restoration, it can take decades before results are realized (IPCC, 2019). If ecosystems are left undisturbed (e.g., through protected or conserved areas), restored habitats can sequester and store carbon over the long term, in addition to providing vital habitat for wildlife. Our analysis provides a preliminary approach to prioritizing restoration initiatives at a national scale—the first phase of a newly proposed multiphase restoration framework for Canada aimed at helping to inform and guide policy makers and practitioners (Mansuy et al., 2020). The following section details some of the many factors that should be considered and improved to move from spatial analysis, into policy and implementation.

4.2 | Caveats and limitations

Given the scale of our analysis, there are some noteworthy caveats and limitations, for which we provide insights regarding how these issues could be remedied to strengthen future iterations of this type of analysis.

4.2.1 | Focus on land conversion

The analysis relies on landcover classifications (particularly lands that have been converted to human-dominated landcover classes) as a proxy for areas that would benefit from restoration nation-wide. Consequently, the analysis does not sufficiently incorporate ecological degradation—for example, due to overexploitation (e.g., industrial activity), pollution, plant diseases or pests, and/or invasive species. As a result, there are some regions of Canada that may be underrepresented in our analysis, that we would have expected to be highlighted more prominently for restoration—for example, in Vancouver Island where harvest disturbance is pronounced (Hermosilla et al., 2016). These logged areas do not fall under the classification of converted lands, as there is a legal obligation for companies with forest tenures to reforest cutblocks subject to the specifications outlined in the *Forest and Range Practices Act* (SBC 2002, C.69, S.29) for British Columbia. Aside from roads and other linear features that often accompany these areas, forests that may be degraded due to harvest are not considered "converted" and were therefore not included within our analysis. Subsequent analyses should attempt to integrate degraded ecosystems to fully capture the need for, and prioritization of, ecological restoration in Canada—recognizing that there is currently a lack of spatial data evaluating ecological degradation for multiple landcover classes at a national scale.

4.2.2 | Inherent assumptions of the model

There are several inherent assumptions of the model that may impact the spatial prioritization of ecological restoration of converted landscapes in Canada. For instance, the results of the current analysis are suggestive of comprehensive restoration success, and do not fully incorporate feasibility, cost or local priorities as considerations for prioritization, which should be done at a finer resolution to yield meaningful results applicable to local levels (Cook-Patton et al., 2021). Similarly, while this analysis is national in scale, policy management and implementation will need to be conducted at smaller geographic extents, including provincial, municipal and community-based levels. Our analysis also assumes that converted land will be available for restoration—an overly positive assumption that could be addressed through an analysis of cultural, social, and economic feasibility. To achieve restoration success in the many areas identified in this analysis, land availability and restoration activities will need to be negotiated with communities and stakeholders to ensure that initiatives align with their priorities and needs. For instance, reconciling economic tradeoffs, food security, and the long-term need for restoring ecosystem functioning (Brussard et al., 2010) in agricultural areas is a complex challenge that will impact the feasibility and cost of implementation, and consequently, where sustainable management may be a more suitable NbCS pathway (e.g., Cook-Patton et al., 2021). Notably, while urban areas were removed from our analysis to prevent potential issues of human displacement, ethical and rights-driven urban conservation efforts can complement our analysis, by bolstering connectivity for wildlife and supporting climate regulation and adaptation at local levels (IPBES, 2019; IPCC, 2022).

From a methodological perspective, we lack a temporal or predictive component to the assessment of restoration potential—meaning that any future disruptions or conversion of landscapes are not currently accounted for. Likewise, the vulnerability of nature to potential disruption (e.g., via development or climate change impacts) and associated release of greenhouse gases to the atmosphere is consequential. Accordingly, incorporation of predictive landcover modeling—including climate change scenarios—could strengthen this analysis for its applicability into the future. Resiliency is also lacking from the biodiversity component, as the analysis hinges on the assumption that wildlife would be capable of moving between restored habitats. Additional components of (i) connectivity between natural landscapes—including a dynamic approach that assessed connectivity as ecosystems are restored—and (ii) accounting for and bolstering climate refugia (e.g., Carroll & Ray, 2021) would also help to facilitate wildlife movement in an era of climate change. Like connectivity, attributes such as the diversity and selection of species would help provide insight into the resiliency of ecosystems (Timpane-Padgham et al., 2017) in addition to climate adaptation, but may be more suited to implementation, rather than spatial prioritization explicitly. Finally, as with many prioritization exercises, it is possible that priorities may overlook some species, habitats and ecozones by directing attention to only areas with a high overlap in key conservation values.

The analysis is specific to enhancing climate change mitigation and biodiversity recovery through ecological restoration, incorporating only national-scale biophysical data. Consequently, cultural values and additional co-benefits—such as the capacity of and demand for ecosystem services (e.g., Mitchell et al., 2021)—are not considered through this spatial prioritization exercise at a national scale. Importantly, local Indigenous knowledge may help inform the objectives and types of restoration needed, the construction of reference ecosystems, and species selection for habitat enhancement—among many other contributions (Uprety et al., 2012). This is particularly noteworthy, given that the current analysis focuses on prioritization of locations for restoration a nationally, and does not address restoration needs and actions, partner engagement and Indigenous support or consent—which will be critical for implementation success in local contexts. Likewise, the equity implications of producing a national map without social data are a growing concern (Löfqvist et al., 2022; Schultz et al., 2022) that reinforce our analysis as one component of a multifaceted approach needed for restoration.

Finally, the analysis does not speak to conservation actions beyond the ecological restoration of converted landscapes. Canada contains over 7M km^2 of the world's remaining wilderness, ranking second only to Russia at a global scale (Allan et al., 2017; Watson et al., 2018), and thus, urgent, and effective protection of these intact ecosystems is also critical to prevent further emissions to the atmosphere—providing immediate impact for climate change mitigation (IPCC, 2019; Seddon et al., 2021). Suitably, the federal government has focused its attention on protecting and conserving 30% of lands and waters by 2030; aligning with international recommendations (Dinerstein et al., 2019; Roberts et al., 2020) and targets (CBD, 2022). However, the potential for and success of NbCS, such as restoration and protected area establishment, can only be achieved alongside rapid decarbonization of the global economy (Seddon et al., 2021).

5 | CONCLUSION

There is an increasing need for integrated conservation actions that address climate change and biodiversity loss simultaneously (IPCC, 2019; Turney et al., 2020). Focusing solely on one environmental issue would be a missed opportunity. While pathways to limit global warming to 1.5°C will require rapid and diverse approaches in every sector, climate mitigation options aligned with nature are critically needed (IPCC, 2018). Not only can ecosystem restoration provide climate mitigation opportunities, but such conservation actions also provide additional benefits for climate adaptation (IPCC, 2018) and the recovery of wildlife (IPBES, 2019). Spatial analyses to identify where such conservation actions would yield the greatest environmental benefits are critical to inform, prioritize, and coordinate conservation action at multiple scales (Soto-Navarro et al., 2020). In the absence of spatial prioritization and optimization information, countries may find it difficult to specify transparent objectives to advance progress on biodiversity and climate change portfolios.

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DATA AVAILABILITY STATEMENT

All data inputs were openly accessible and can be accessed from their respective sources. Final data products are accessible online via Figshare. Scripts for running the analysis can be accessed upon request from the authors. https://doi.org/10.6084/m9.figshare.20344044.v1.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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