Title: Maximizing Nature-based Solutions using Artificial Intelligence to align global biodiversity, climate, and water targets.

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Summary

Nature-based Solutions (NbS) can represent holistic pathways to reach sustainable biodiversity, climate, and water outcomes through conservation and restoration. Yet, existing prioritization frameworks rarely identify holistic NbS that maximize these outcomes. Here, we present an AI-driven framework that prioritizes NbS locations, maximizing biodiversity protection with ecological intactness, carbon storage, and water surface stability. We implement this framework through scenarios combining specific biodiversity and co-benefits outcomes to achieve Canada's 30x30 conservation and restoration targets. Our results reveal inevitable environmental trade-offs and critical implications for equitable NbS and extractive activities. To achieve conservation targets, protecting threatened biodiversity and irrecoverable carbon storage in forests would effectively address trade-offs and enhance Protected Areas outcomes. However, minimizing trade-offs to achieve restoration targets will require targeted interventions in existing forested and agricultural lands. These findings demonstrate that frameworks integrating AI and biodiversity-co-benefit scenarios reveal strategic land use planning, policies, and investments for holistic NbS.

Keywords

Biodiversity, carbon stocks, surface water, conservation, restoration, nature-based solutions, spatial prioritization, reinforcement learning, artificial intelligence, Canada

Introduction

Global biodiversity loss is closely intertwined with climate change, water scarcity, and social inequality. Given these interconnections, many global targets emphasize the

need for holistic pathways that simultaneously address environmental and social challenges. Centered around biodiversity, the Kunming-Montreal Framework aims to restore 30% of degraded land and establish 30% of area-based conservation by 2030 (i.e., 30x30 targets), ensuring enhanced biodiversity, ecosystems' integrity, and related co-benefits [1]. Since the establishment of the Paris Agreement [2], reducing land use emissions while conserving and restoring ecosystems' carbon sinks have become relevant components of Nationally Determined Contributions (NDCs) to reach net-zero emissions by 2050. Similarly, the Sustainable Development Goals (SDGs) set targets to protect and restore ecosystems, including water-related ecosystems such as forests, wetlands, rivers, and lakes [3].

Nature-based Solutions (NbS), understood as actions to protect, restore, or sustainably manage ecosystems (natural or modified) to address societal challenges [4], may play a critical role in reaching global targets. NbS encompass a wide set of interventions [5,6], many of which provide holistic pathways for countries to reach the 30x30 conservation and restoration targets [1] in synergy with climate change mitigation [7], water management [8], and Sustainable Development Goals [9]. Reaching these global targets through NbS implies strategically aligning biodiversity outcomes with related co-benefits emerging from ecological integrity, carbon storage, and water. This alignment will necessarily invoke trade-offs and NbS monitoring frameworks that can identify optimal conservation and restoration priorities.

Over the past decade, analytical tools for NbS implementation have become increasingly available. State-of-the-art monitoring tools typically leverage field observations, remote sensing, and machine learning to predict spatial-temporal patterns of biodiversity [10], carbon stocks [11,12], and water quality [13]. In parallel with this increased monitoring capacity, other approaches identify optimal NbS priorities for conservation and restoration actions. Usually, conservation priority frameworks have weighted the importance of biodiversity aspects such as irreplaceability (e.g., species and habitats rarity) and vulnerability through a reactive (e.g., threatened species, habitat loss) or proactive (low vulnerability and low cost) approach [14,15]. From an ecosystem services perspective, Mitchell et al.[16] instead prioritized conservation co-benefits emerging from carbon storage, water supply, and tourism. Others have aimed to inform conservation targets by simultaneously prioritizing biodiversity outcomes with climate suitability [17–19], carbon storage [20], or multiple co-benefits simultaneously [21,22].

The identification of optimal NbS has not been restricted to conservation targets. For instance, biodiversity and carbon outcomes have been ranked and prioritized on lands that have been converted to pastures and croplands [23]. Vettorazzi & Valente[24] proposed land suitability assessments for prioritizing restoration actions that could improve water supply. A common approach between conservation [25] and restoration [26] has resulted from prioritizing vulnerability (e.g., habitat conversion, human footprint) on global ecoregions. However, AI's potential to find optimal solutions has only recently begun to be explored in conservation [27] and restoration [28] priority frameworks. Furthermore, few studies leverage AI to develop common frameworks for conservation and restoration targets that maximize outcomes related to biodiversity as well as related co-benefits.

The complexity of optimizing biodiversity and co-benefit outcomes for conservation and restoration targets is further challenged by the interplay of local and economic priorities. Governments and decision-makers have dominated conservation and restoration planning and decision-making spaces, relegating local priorities and capacities [29]. This is the case of Indigenous Peoples, who have been historically marginalized from these spaces [30] despite being increasingly acknowledged in global environmental targets [1–3]. Indigenous Peoples' presence in 40% of global protected areas [31] and 36% of intact forests [32] suggest that any feasible and equitable pathway for conservation and restoration targets requires the inclusion of Indigenous land governance.

Economic priorities also challenge the feasibility of conservation and restoration targets. For example, some priority frameworks highlight the restoration potential of converted lands for pasture and agriculture to reach environmental targets [23,28]. However, realizing this potential may be unfeasible due to economic barriers [33] and may require considering other degraded lands to reach restoration targets. Similarly, prioritizing energy development will limit governments' pathways to achieve environmental targets while diminishing current biodiversity and co-benefits outcomes [34–36]. Tackling this complexity requires prioritization frameworks that explore diverse conservation and restoration pathways and that address their local and economic impacts.

Here, we present a framework that prioritizes NbS locations maximizing biodiversity and co-benefits outcomes to reach 30x30 conservation and restoration targets. Leveraging Reinforcement Learning, this framework trains an agent to learn from the state of a system (i.e., exploration) and cost-effectively select areas (i.e., exploitation) that maximize a reward (Figure 1). A cost-effective selection follows monitoring (e.g., species occurrence) and prioritization (e.g., minimize species loss) policies while avoiding a predefined cost (e.g., low ecological intactness). We test this framework in Canada under a series of conservation and restoration scenarios that maximize the occurrence of threatened species in synergy with co-benefits from ecological intactness, irrecoverable carbon storage, and water surface stability. Additionally, we examine some local and economic implications of these scenarios. Overall, aligning biodiversity outcomes with other co-benefits across conservation and restoration scenarios results in varied environmental trade-offs and spatial alignments with Indigenous-led NbS and natural resource projects. To conserve 30% of lands, prioritizing the protection of threatened biodiversity and carbon stocks in forests can effectively address these trade-offs. Yet, minimizing trade-offs to restore 30% of degraded lands will require a combination of scenarios and interventions in existing forested and agricultural lands. Taken together, this prioritization framework demonstrates that integrating AI, multiple co-benefits, and scenario analysis can reveal strategic land use planning, policies, and investments for holistic NbS.

Results

Scenarios to conserve 30% of land by aligning biodiversity, climate, and water outcomes.

We defined conservation priority scenarios (Figure 1) based on the spatial distribution of existing Protected Areas (Figure S1), threatened species (Figure S2), ecological intactness, carbon storage, and water surface stability (Table S1). The conservation scenarios identified an additional ~17.75% of Canadian land areas to be protected. These scenarios achieve Canada's 30X30 targets by maximizing the protection of threatened biodiversity and guaranteeing at least 10% of each threatened species range, while also prioritizing co-benefits of ecological intactness (Conservation Scenario 1), irrecoverable carbon stocks (Conservation Scenario 2), and water surface stability (Conservation Scenario 3) (Figure 2).

When only ecological intactness was prioritized (Conservation Scenario 1; Figure 2), more than 60% of conservation priorities were concentrated in the Southern and Northern Artic (Quebec, Nunavut, Northwest Territories). Relative to existing Protected Areas, this scenario would result in an expected increase of ecological intactness from 0.80 to 0.91 on a normalized scale. However, it would reduce the mean number of threatened species protected (2.55 to 1.52 species/100 km^2), species richness (76.49 to 40.58 species/100 km2), carbon stocks (441.42 to 145.43 tC/ha), and absolute water surface change (2.30%/100 km^2 in 2000-2015 vs 1984-1999) (Figure 3).

Conservation Scenario 2 (prioritizing irrecoverable carbon stocks; Figure 2) led to conservation priorities that are concentrated in the forest-dominated Boreal ecozones (> 60%) and the Montane Cordillera (~14%) throughout southern and western provinces, respectively. In contrast to Scenario 1, aligning biodiversity and climate change mitigation targets led to lower ecological intactness (0.74) but consistently higher number of protected threatened species (3.42 species/100km^2), species richness (95 species/100km^2), water surface change (0.67%), and carbon stocks (631.34 tC/ha), compared to Protected Areas (Figure 3).

Conservation Scenario 3 that prioritized water surface stability (Figure 2), had a dispersed geographic distribution, partially overlapping with Conservation Scenarios 1 and 2. However, some priorities were particularly aggregated in the eastern Taiga Shield (Northern Quebec and Newfoundland and Labrador), Hudson Plains (Quebec and Ontario), and Taiga Plains (British Columbia), known to be partially dominated by peatlands. Except for an overall reduction of water surface change, Scenario 3 exhibited similar outcomes to existing Protected Areas.

After overlapping the results from all three conservation scenarios (Figure 2), we were able to identify the areas of land that were prioritized in two or more of the individual scenarios. Of the target 17.75% of land area prioritized by the three scenarios, 11.4% appeared in two scenarios and 0.89% in all three scenarios, suggesting significant potential for achieving multiple co-benefits. The conservation scenarios overlaps also reveal a reduced portion of priorities in strategic ecozones with substantial outcomes on biodiversity, ecological intactness, carbon stocks, and water stability co-benefits. For

example, compared to existing Protected Areas, the overlapped priorities in the Mixewood Plains (0.01%), Pacific Maritime (0.1%), and Hudson Plains (13.2%) (Figure S3) would simultaneously increase biodiversity outcomes, ecological intactness, and carbon stocks (Table S2). The overlaps also highlight three conservation priorities clusters that could potentially realize biodiversity and co-benefits outcomes. These clusters are the ecozone transition of the Montane Cordillera, Boreal Plains, and Taiga Plains (British Columbia); the southern Hudson Bay and James Bay Lowlands (i.e., Hudson Plains, Québec, Ontario); and Lac Temiscamingue Lowlands (i.e., Boreal Shield, Québec, Ontario). Overall, these Conservation Scenarios imply that aligning biodiversity outcomes with other co-benefits results in varied spatial patterns of conservation priorities and trade-offs between co-benefits. Despite these trade-offs, maximizing the protection of threatened biodiversity and irrecoverable carbon stocks (Conservation Scenario 2) represents a comprehensive pathway to improve biodiversity, climate change mitigation, and water stability outcomes in existing Protected Areas.

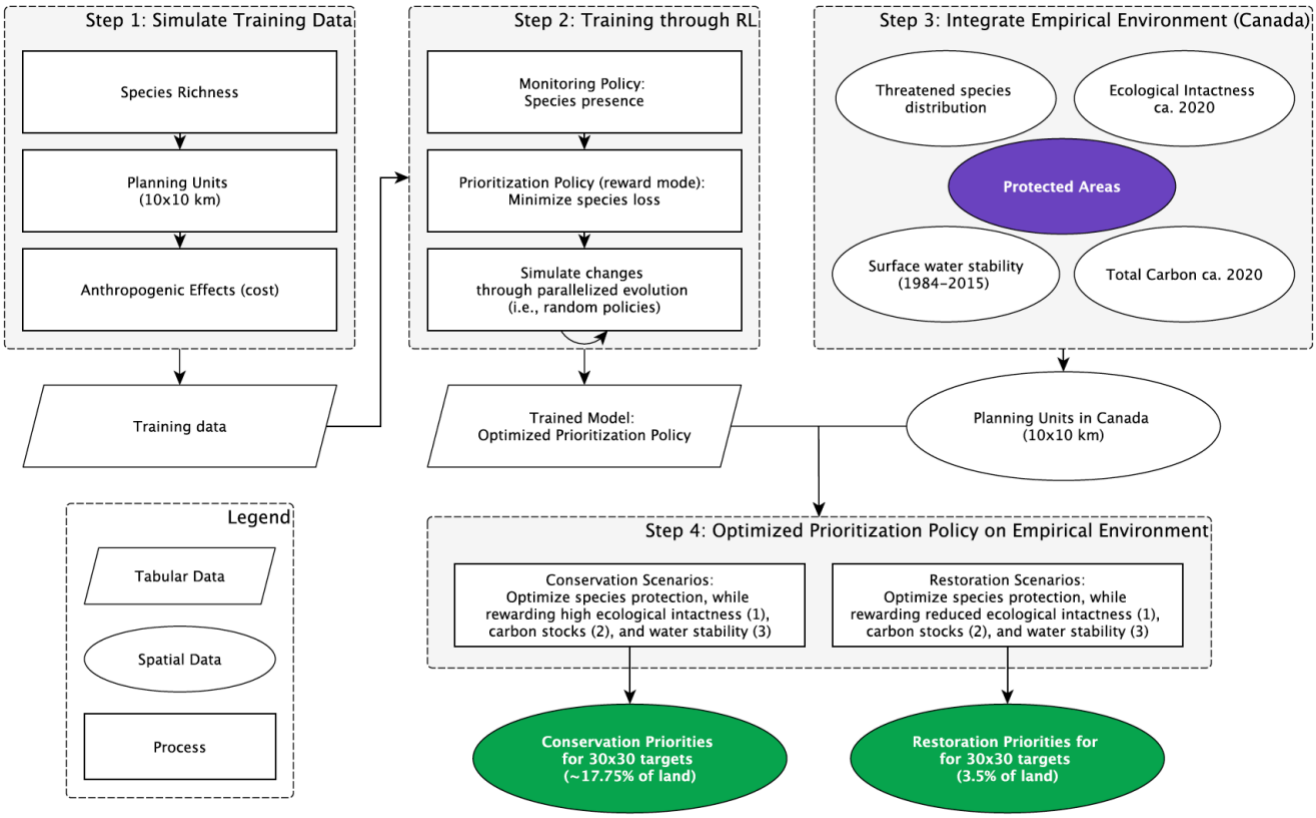

Figure 1. Flowchart summarizing the steps to identify Conservation and Restoration priorities to reach 30X30 targets aligned with co-benefits, using Reinforcement Learning.

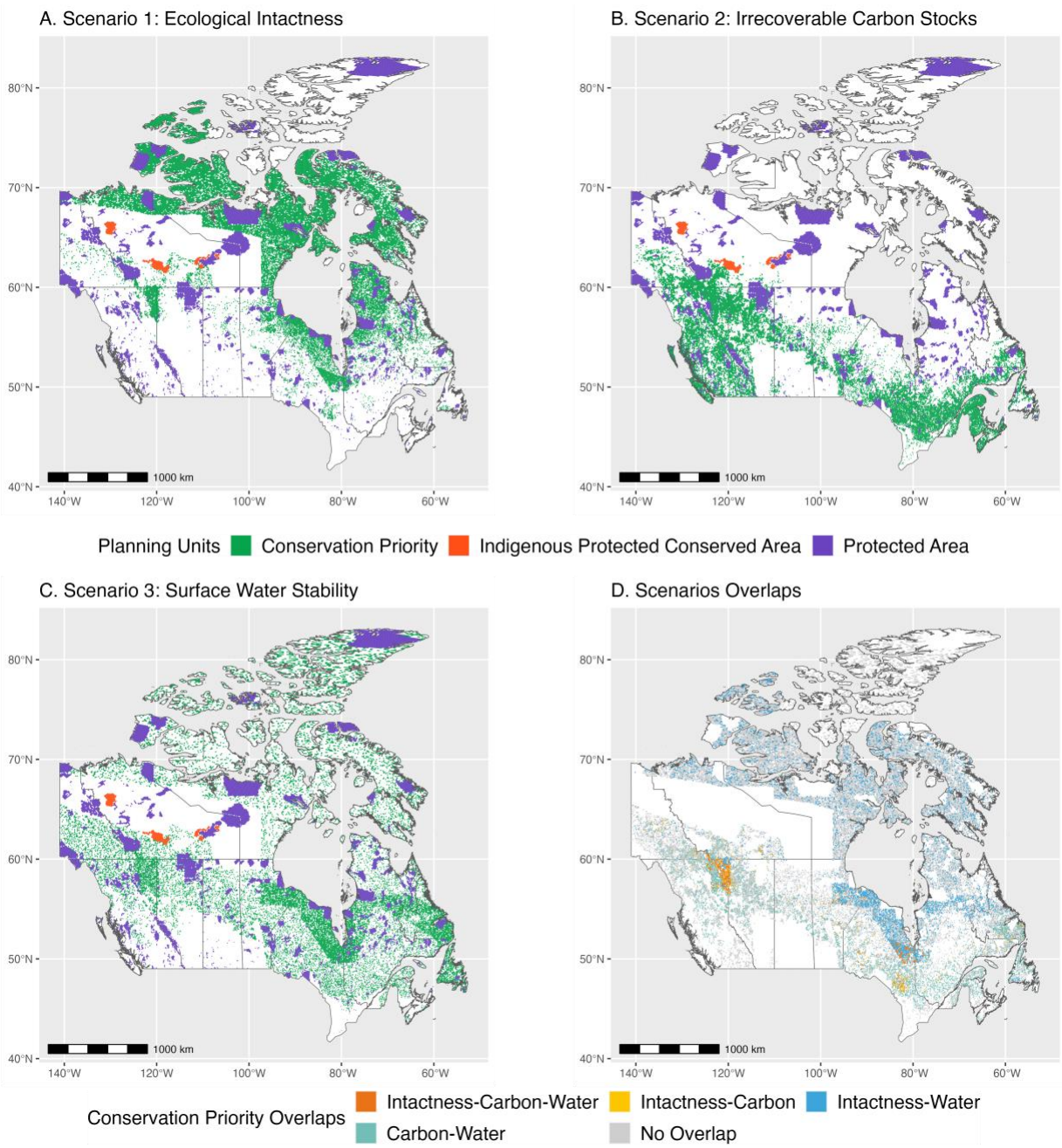

Figure 2. The spatial distribution of Conservation Priority Scenarios to reach 30X30 targets obtained through Reinforcement Learning. All Scenarios assume a baseline extent of Protected Areas of 12.25% and a 17.75% remaining area budget to maximize the occurrence of threatened species with co-benefits emerging from Ecological Intactness (A), Irrecoverable Carbon Stocks (B), Water Surface Stability (C). Priority Areas had a 10km resolution. The Scenarios Overlaps (D) suggest areas that simultaneously maximize the occurrence of threatened species with multiple co-benefits.

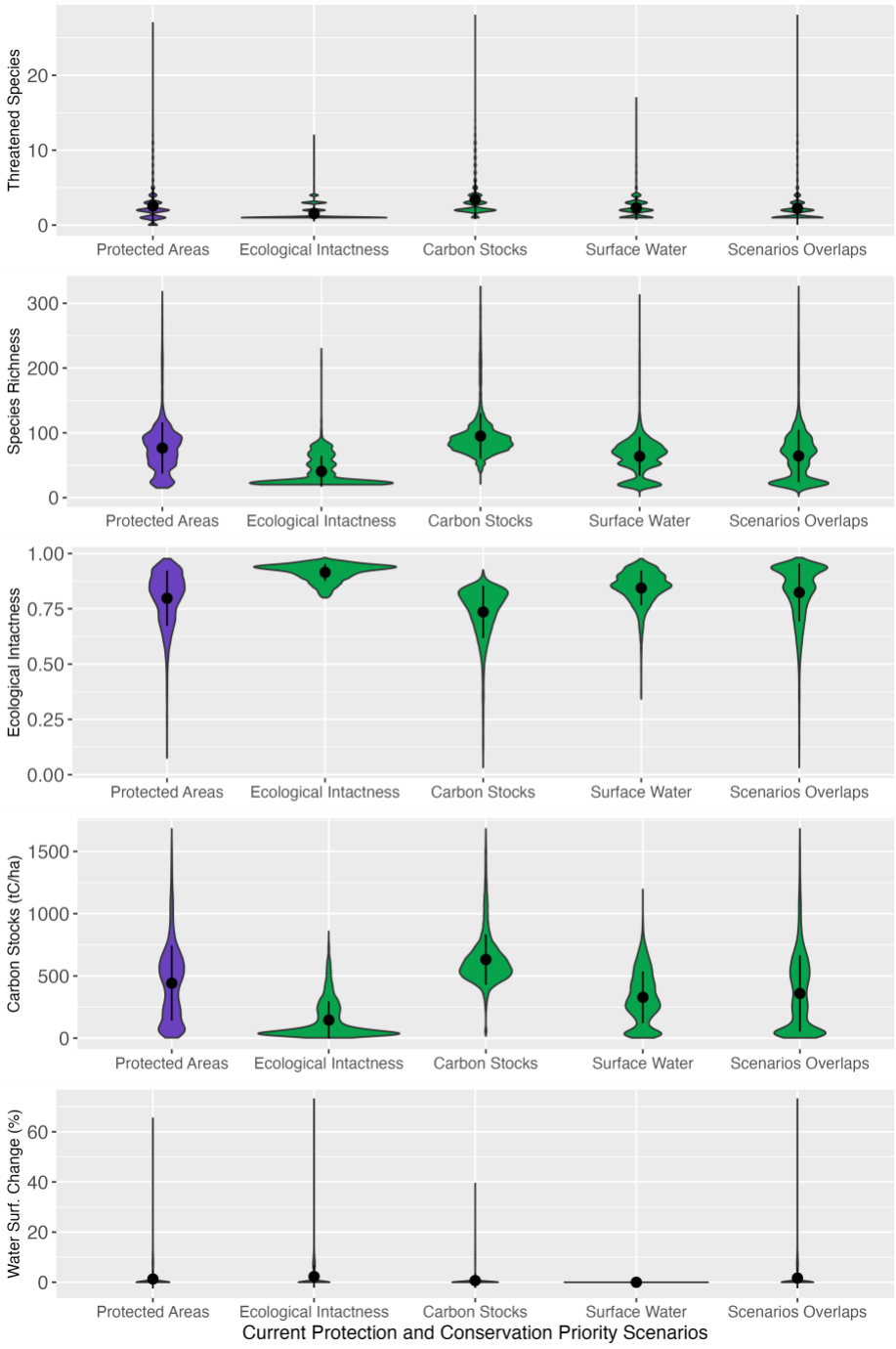

Figure 3. The distribution of threatened species, species richness, ecological intactness, carbon stocks, and absolute surface water change in existing Protected Areas and Conservation Priority Scenarios. The conservation scenarios aim to maximize the occurrence of threatened species with co-benefits emerging from Ecological Intactness, Irrecoverable Carbon Stocks, and Water Surface Stability. The Scenarios Overlaps represent the co-occurrence of conservation priorities in at least two scenarios. The points and bars refer to the mean and standard deviation.

Scenarios to restore 30% of degraded land by aligning biodiversity, climate, and water outcomes.

The restoration scenarios suggested priorities in 30% of degraded land (i.e., ~3.5% total surface) that would maximize the occurrence of threatened biodiversity in areas experiencing reduced ecological intactness (Restoration Scenario 1), carbon stocks losses (Restoration Scenario 2), and water surface instability (Restoration Scenario 3) (Figure 4). Restoration Scenario 1 priorities were mostly concentrated in the Prairies (~72.8%) and Mixed Wood Plains (~12.4%) that are dominated by agriculture. Among all Restoration Scenarios, this scenario was particularly effective for protecting threatened biodiversity (~4) and species richness in general (108) and the least effective for carbon storage (147.48 tC/ha) (Figure 5). When threatened biodiversity was prioritized with irrecoverable carbon stocks losses, a considerable part of the priorities occurred in the Boreal Shield (31.8%), Montane Cordillera (22.2%), and Boreal Plains (21.3%), largely dominated by forests (Figure 4). Although Restoration Scenario 2 would result in lower biodiversity outcomes than Restoration Scenario 1, prioritizing the recovery of carbon stock losses exhibit the most effective outcomes for ecological intactness (0.70), carbon stocks (513.94 tC/ha), and water surface stability (1.2%) (Figure 5). The restoration scenario 3 displayed a wide geographical range of priorities across contrasting ecozones (Figure 4, Figure S3). However, we did not identify wide-scale improvements in multiple outcomes after prioritizing actions for threatened biodiversity and water surface instability.

The overlaps among Restoration Scenarios represented approximately a third (1.28%) of the desired land target (3.5%). Specifically, 0.05% simultaneously aligned reduced ecological intactness, carbon storage, and water co-benefits, and 1.23% aligned two of these co-benefits. Consequently, we did not identify wide potential or spatial clusters (Figure 4), requiring coordinated actions to improve biodiversity and all co-benefits (Figure 5). Nevertheless, some overlapped restoration priorities that moderately clustered across the western Boreal Shield and eastern Montane Cordillera (British Columbia) (Figure 4) suggest moderate effects on threatened species (~3 species/100 km^2) and species richness (90-110 species/100 km^2) if aligned with the restoration of ecological intactness and carbon stocks (Figure 5, Table S3). Restoring these co-benefits would potentially result in larger biodiversity outcomes in the Mixedwood Plains from Southern Ontario, which also displayed a cluster of overlapped priorities. In the Prairies (Alberta, Saskatchewan, Manitoba), a cluster of overlapped priorities suggested that aligning restoration actions that manage and adapt to water surface instability and improve ecological intactness could positively impact threatened species (~3) and several species in general (91). These spatial patterns imply that each restoration scenario would potentially improve conditions for threatened biodiversity in tandem with one or multiple co-benefits in limited spatial extents, suggesting diverse and context-dependent restoration pathways.

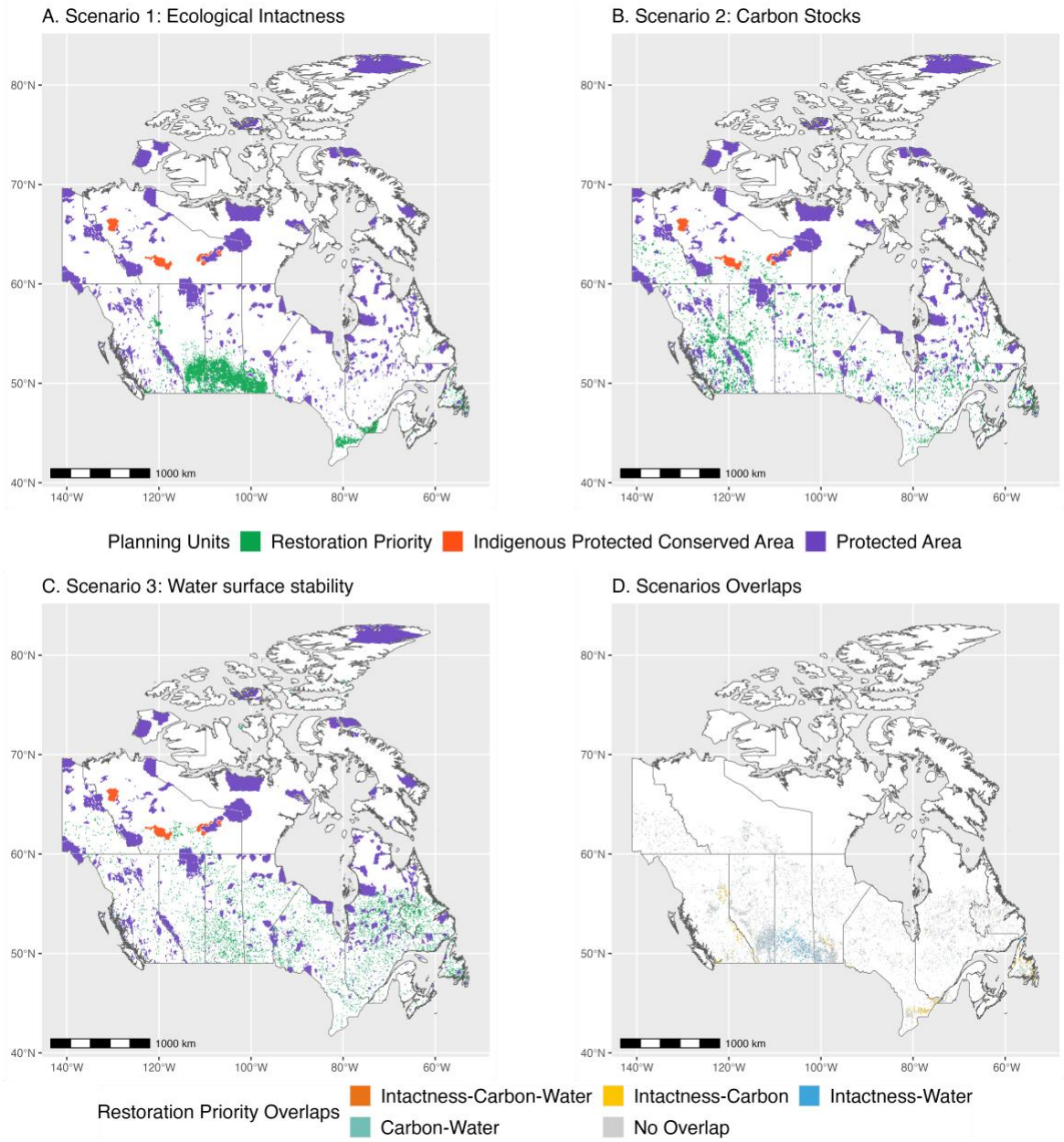

Figure 4. The spatial distribution of Restoration Priority Scenarios to reach 30X30 targets obtained through Reinforcement Learning. All Scenarios assume a baseline extent of degraded land of 11.7% and an area budget of 3.5% to maximize the occurrence of threatened species while prioritizing the occurrence of low ecological intactness (A), irrecoverable carbon stocks losses (B), and water surface instability (C). Priority Areas had a 10km resolution. The Restoration Scenarios overlaps (D) suggest areas that maximize the occurrence of threatened species and are currently experiencing reduced ecological intactness, carbon stocks losses, and water surface instability.

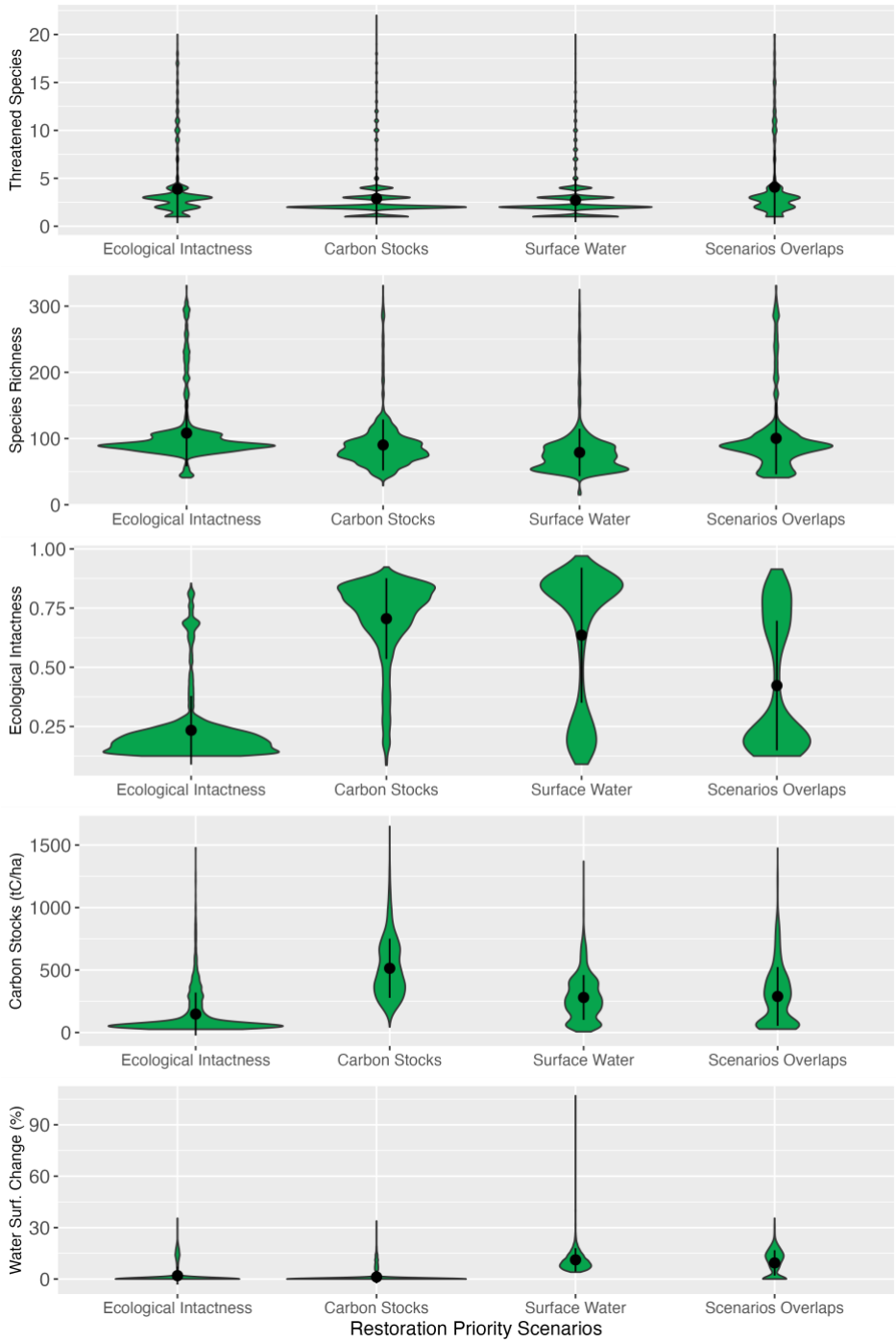

Figure 5. The distribution of threatened species, species richness, ecological intactness, carbon stocks, and absolute surface water change intensity in restoration priority scenarios to reach 30X30 targets. All restoration scenarios aim to maximize the occurrence of threatened species while prioritizing the occurrence of low ecological intactness, irrecoverable carbon stocks losses, and water surface instability. The Scenarios Overlaps represent the co-occurrence of conservation or restoration priorities in at least two scenarios. The points and bars refer to the mean and standard deviation.

Conservation and restoration priorities are near Indigenous-led NbS and major natural resource projects.

To identify the local implications of the priority scenarios, we quantified the overlap and distance of Indigenous-led NbS programs and other Indigenous Lands to conservation and restoration priorities (Figure 6, Table S4). Indigenous-led NbS included Indigenous Protected Conserved Areas and the Indigenous Guardians Federal Program. These federally supported initiatives displayed the highest overlap (47%) and closest proximity (130 km) to conservation priorities maximizing Irrecoverable Carbon stocks (Scenario 2). Conversely, priorities maximizing Ecological Intactness (Scenario 1) showed minimal overlap (8%) and the greatest distance (~180 km). Similarly, Restoration priorities focusing on Carbon Stocks recovery (Restoration Scenario 2) demonstrated the highest overlap (17%) and shortest distance (~150 km) to Indigenous-led NbS. Notably, these carbon stocks focused Conservation and Restoration priorities, displaying more proximity to these government-funded initiatives, mainly occurred in the Pacific and Atlantic Maritimes, the Montane Cordillera and Hudson Plains.

Compared to Indigenous-led NbS, other Indigenous Lands without federal government funding were considerably closer to Conservation and Restoration Priorities. The overlap of Indigenous Lands with Conservation priorities ranged between ~34% (Conservation Scenario 2: Irrecoverable Carbon Stocks) and ~3% (Conservation Scenario 1: Ecological Intactness) and an average distance range of 48 km to 160 km (Figure 5). For Restoration priorities, other Indigenous Lands showed 12-23% overlap and averaged ~80 km in distance. These spatial patterns imply that a significant fraction of government-funded Indigenous-led NbS overlap or are near conservation and restoration priorities, especially those that align with climate change mitigation. Additionally, both conservation and restoration priorities, which displayed disparate spatial patterns across ecozones, share a wide alignment with Indigenous Lands that lack government funding.

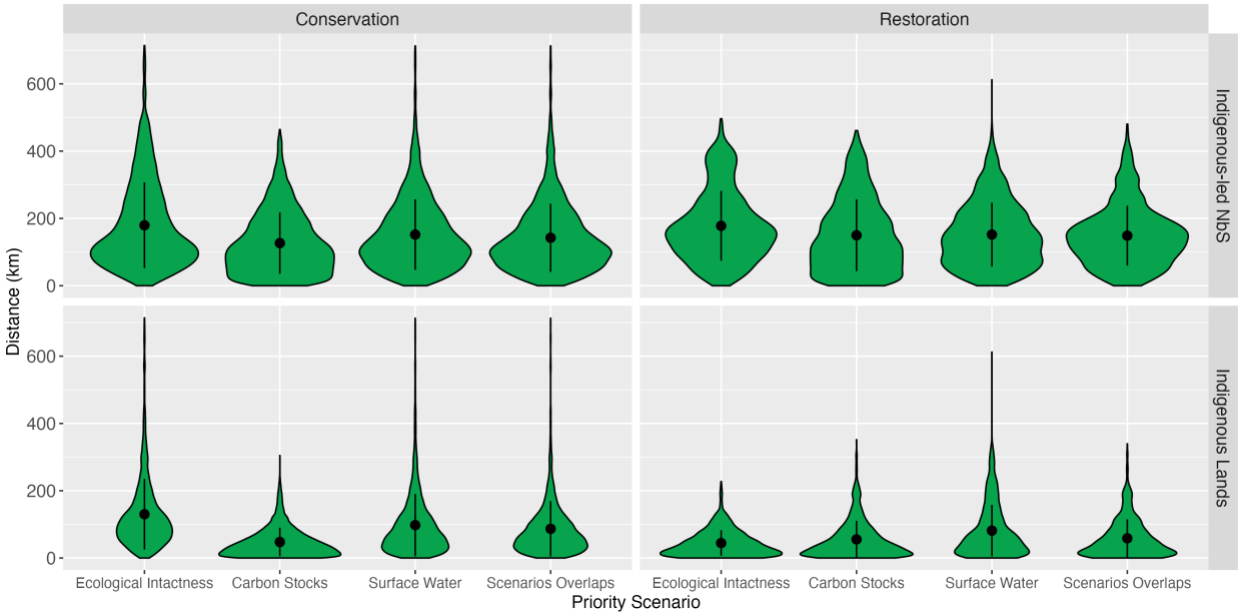

Figure 6. The distribution of conservation and restoration priorities distance to Indigenous-led NbS and other Indigenous Lands. Indigenous-led NbS corresponded to government-recognized Indigenous Protected Conserved Areas and the Indigenous Guardians Federal Program. Other Indigenous Lands corresponded to areas that are not federally funded in Indigenous-led NbS programs. The points and bars refer to the mean and standard deviation.

Finally, we assessed the spatial distribution of conservation and restoration priority scenarios in relation to major forestry, mining, and energy sector projects under construction or planned in the next ten years (Figure 7). The average proximity of forestry projects to restoration priorities (~370-380 km) tended to be higher than conservation priorities (~340-880 km). Compared to forestry, conservation priorities were, on average, closer (140-450 km) to energy projects (i.e., solar, hydro, and oil), particularly when ecological intactness, carbon stocks, and water stability co-benefits were overlapped (i.e., Scenarios Overlaps). Notably, conservation priorities were very close to energy projects in the Boreal Plains, Montane Cordillera and Pacific Maritimes. Moreover, the average distance of all restoration priorities to energy projects was the lowest (83-120 km) among all scenarios and sector comparisons. In fact, 25% of the restoration scenarios that prioritized low ecological intactness (Restoration Scenario 1), carbon stock losses (Restoration Scenario 2), and scenarios overlaps were in the 30 km of an energy project. Relative to energy projects, restoration priorities shared ecozone locations with conservation priorities but were additionally identified in the Mixewood Plains and Prairies. Furthermore, energy linear infrastructure, in particular, displayed the most significant overlap (1-4%) with both conservation and restoration priorities (Table S5).

The distance of mining projects to conservation and restoration priorities tended to be higher than energy projects but lower than those corresponding to forestry (Figure 7). For example, the average conservation priority that maximized the protection of threatened biodiversity and ecological intactness (Conservation Scenario 1) was ~130

km from mining projects, and 25% of these priorities were in a ~80 km range. Restoration priorities across the different scenarios were in a similar average range to mining projects (~160 km). Moreover, the spatial distribution of both conservation and restoration priorities to mining was relatively similar to energy projects across Boreal ecozones and the Prairies. According to these spatial distributions, restoration priorities across all scenarios are more likely to be close to major natural resource projects than conservation priorities, especially in the energy sector. Nevertheless, some conservation priorities that maximize ecological intactness (Conservation Scenario 1), irrecoverable carbon stocks (Conservation Scenario 2), and overlapped co-benefits exhibit a marked immediacy to major energy and mining projects.

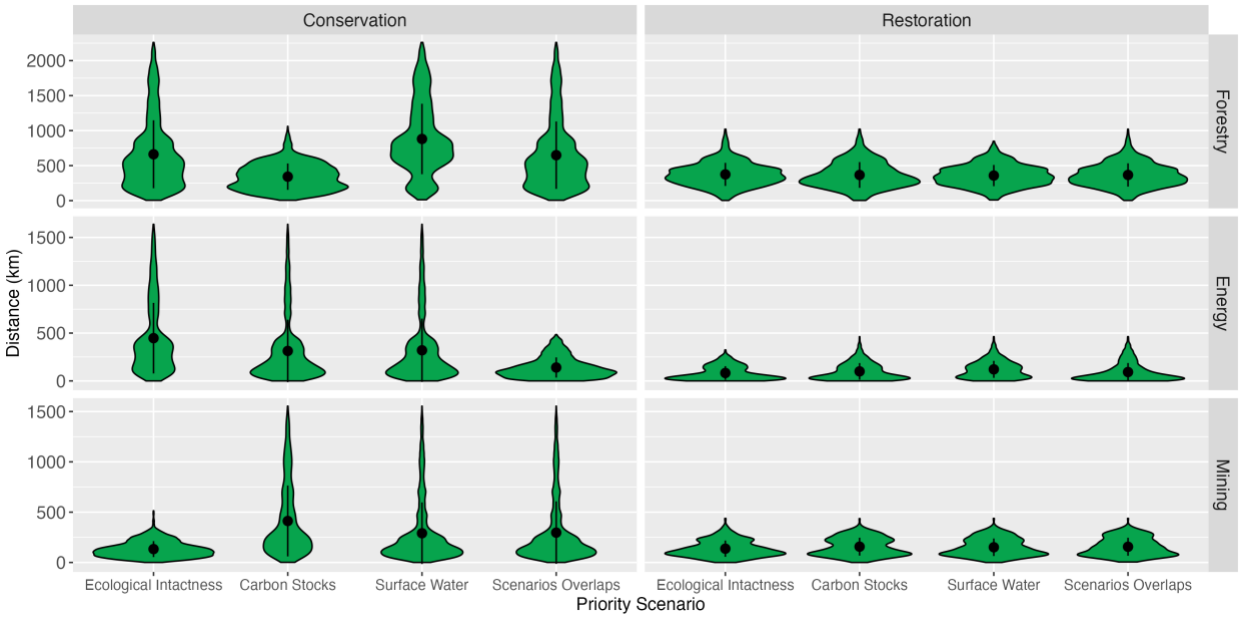

Figure 7. The distribution of conservation and restoration priorities distance to major natural resource projects in the forestry, energy, and mining sectors. The points and bars refer to the mean and standard deviation.

Discussion

Our study strengthens a growing body of research aiming to inform the impactful implementation of Nature-based Solutions. Leveraging Reinforcement Learning, we provide a prioritization framework assessing conservation and restoration scenarios that maximize threatened biodiversity protection in synergy with co-benefits from ecological intactness, carbon storage, and water (Figure 1). Moreover, we analyze some local and economic implications of these scenarios. We test this holistic framework in the context of Canada's 30x30 conservation and restoration targets stated in the Kunming-Montreal Global Biodiversity Framework. The results exhibit complex environmental trade-offs along with potential synergies, demonstrating how Artificial Intelligence can help optimize conservation and restoration decisions. By testing the framework at the national level, we show its versatility in incorporating various environmental co-benefits and scenario analyses to inform pathways to reach environmental targets in different

land use contexts and scales. Particularly, this framework versatility reveals combinations of conservation and restoration scenarios that maximize both biodiversity protection and environmental co-benefits.

Holistic pathways to reach 30x30 conservation targets

Our results highlight opportunities to reach 30x30 conservation targets that improve biodiversity while maximizing co-benefits. Currently, our results confirm that the existing Protected Areas network in Canada does not effectively protect threatened and non-threatened species [19] and only partially captures the potential co-benefits from carbon storage and water [16]. These results are not exclusive to Canada and reflect a known global trend where Protected Areas are biased to locations with reduced land-use pressures that do not necessarily prioritize biodiversity and other co-benefits outcomes [37].

To improve Protected Areas outcomes, our results show that prioritizing the protection of threatened biodiversity and irrecoverable carbon stocks yields the highest improvements in biodiversity and co-benefits. Expanding the Protected Areas network with this prioritization approach could maintain ecological intactness (i.e., species abundance, habitat quality) and lead to improved carbon storage and surface water stability. Most of these priorities are located in southern provinces, extending across forest-dominated lands in the boreal ecozones to the western Montane Cordillera. Without accounting for biodiversity, Mitchell et al.[16] have already suggested the potential of these ecozones for carbon storage, water provision, and nature-based recreation. Although not assessed in our analysis, these forest lands serve as climate refugia for multiple taxonomic groups, including vertebrates, plants, and invertebrates [17,18]. Our results, therefore, demonstrate that conservation targets can be effectively maximized with avoided land use emissions targets in forested lands while also achieving co-benefits from ecological intactness and water.

Our prioritization framework also identified locations that simultaneously maximize biodiversity, irrecoverable carbon storage, ecological intactness, and water outcomes. These win-win conservation priorities could moderately contribute to 30x30 conservation targets. Some are dispersed in the Mixewood Plains and Pacific Maritimes and surpass biodiversity outcomes in the Boreal ecozones and Montane Cordillera. These ecozones may guarantee the occurrence of climate-resilient species [19] but contain regions under high anthropogenic pressures (e.g., St. Lawrence Lowlands, Manitoulin Lake Simcoe, Lake Erie Lowland) [38]. Other priority locations were clustered: the southern Hudson Bay and James Bay Lowlands (Quebec and Ontario Hudson Plains); the Lac Temiscamingue Lowlands (Ontario Boreal Shield); and the ecozones transition of the Montane Cordillera, Taiga, and Boreal Plains (British Columbia). The ecozones transition, in particular, may strategically increase the connectivity of Protected Areas in the Yellowstone to Yukon corridor [39]. Moreover, these biodiversity and co-benefits clusters have been identified as either climate corridors or refugia [17,18]. Although strategically important, these win-win conservation priorities remain vulnerable to pervasive climate pressures. This challenge urge exploring suitable adaptive actions,

such as the reduction of land use pressures [40,41], fire prescription [42,43], translocating or slowing dispersal of species, along with other forms of ecosystem engineering [41,44].

Holistic pathways to reach 30x30 restoration targets

Compared to conservation, the restoration priority scenarios suggest diverse and context-dependent pathways to reach the 30x30 targets. We identify that biodiversity outcomes are potentially maximized by restoring areas experiencing reduced ecological intactness in the Prairies and Mixewood Plains that are currently dedicated to agriculture. These ecozones have already been highlighted for their potential biodiversity outcomes for both conservation [19] and restoration [28] targets. More aligned with the latter, our results indicate that these heavily disturbed landscapes are suitable for diverse interventions. For instance, avoiding further grassland conversion into cropland, maintaining shelterbelts, and increasing tree intercropping and silvopasture are essential actions to reduce anthropogenic pressures on biodiversity and the delivery of co-benefits [45,46]. Additional interventions include restoring wetlands [47] and riparian corridors across grasslands and croplands [48], which are expected to improve biodiversity outcomes and water co-benefits (e.g., water provision and quality). These restoration actions are of particular importance in the Prairies, where we identified that aligning restoration actions to manage water surface instability and improve ecological intactness could positively impact local biodiversity. Evidently, small to medium-scale interventions alone may not achieve restoration targets. Nevertheless, moderately improving biodiversity and co-benefits by combining management and restoration interventions can lead to direct benefits for agricultural production [49].

In addition to small and medium-scale interventions, our results show the potential for large-scale interventions in the Prairies and Mixewood Plains to achieve restoration targets. The significant losses of carbon stocks in the Prairies and Mixewood plains due to agriculture represent one of the largest opportunities to simultaneously restore carbon and biodiversity in Canada [28]. However, this restoration potential carries some caveats. The prairies are not extensive climate refugia or corridors [17–19], and the Mixewood Plains are expected to experience increased climate instability [50]. Furthermore, given the need to maintain food production, shifting land use in most of these areas might be unfeasible [6,45], limiting the scale of restoration actions. Addressing climate pressures and safeguarding food production will require further prioritization scenarios at higher resolutions that account for opportunity costs [33]. Consequently, while agricultural lands are fundamental priorities for biodiversity, there are also inherent tradeoffs that would need to be addressed to realize any substantial contribution to Canada’s 30x30 restoration targets.

In contrast to frameworks focusing on converted lands for pasture and agriculture [23], we identify complementary restoration pathways in forested lands. These restoration pathways emerge when biodiversity outcomes were prioritized with the loss of irrecoverable carbon stocks. Most priorities are dispersed across Boreal ecozones and the Montane Cordillera, mirroring previous findings on restoration scenarios for biodiversity and carbon [28]. Restoring carbon storage in forested lands produced slightly lower biodiversity outcomes than restoration scenarios prioritizing agricultural lands.

However, considerable levels of ecological intactness would be maintained by restoring carbon storage in forested lands. If ecological intactness is maintained, combining interventions within and around remaining forests, such as improved forest management and restoring forest cover, could result in short-term benefits for biodiversity [51]. Additionally, restoring and mitigating further carbon stocks losses in these forest lands would result in longer-term climate benefits than restoration actions in agricultural lands [52]. Considering that most of these restoration priorities are near conservation priorities, coordinating efforts at different government levels [53,54] and investments from the public and private sectors [33] will be essential.

Local and economic implications of conservation and restoration pathways

Any pathway to achieve conservation and restoration targets will be intrinsically related to Indigenous land governance. According to our priority scenarios, Indigenous-led NbS currently funded by the federal government (e.g., Indigenous Guardians, Indigenous Protected Conserved Areas) are already playing a key role in protecting biodiversity, irrecoverable carbon storage, and other co-benefits in the Pacific and Atlantic Maritimes, the Montane Cordillera and Hudson Plains. This is the case of the Guardian Watchmen program in the Pacific, which has enhanced local capacity for monitoring environmental change and facilitated co-management arrangements [55]. Interestingly, both conservation and restoration priorities in forested and agricultural lands are closer to currently unfunded Indigenous Lands than government-funded Indigenous-led NbS.

It is worth emphasizing that our analysis likely underestimates the influence of Indigenous Land governance in conservation and restoration. First, we use government-recognized Indigenous Lands locations that do not entirely represent the extent of Indigenous Land governance [30]. Second, several Indigenous Guardians and Indigenous Protected Areas are not recognized or funded by the Federal Government [56]. Additionally, the federal government Initiative Canada Target 1 Challenge [57], which explores the establishment of Indigenous Protected Conserved Areas, is not included in our study and could increase the influence of Indigenous-led NbS on conservation and restoration priorities. Nevertheless, it remains the case that the proximity of conservation and restoration priorities to Indigenous Lands exhibits an opportunity for equitable NbS implementation. To realize this opportunity within the 30x30 targets, governments at different levels need to coordinate efforts that assert Indigenous governance [58–61].

Along with navigating environmental trade-offs and land governance coordination, achieving effective 30x30 targets may also result in land use conflicts with major natural resource projects. Forestry is well known to have impacted forested lands, especially in the Boreal ecozone [62]. However, only a fraction of planned forestry concessions were close to conservation and restoration priorities that maximize biodiversity and carbon outcomes. Instead, energy and mining are the most immediate pressures for these priorities in forested lands. The Peace, Trans Mountain, and other pipelines planned across Alberta and British Columbia ecozones transition represent a challenge for numerous conservation and restoration priorities, including those maximizing multiple co-benefits. This linear infrastructure causes landscape fragmentation, species

mortality, and changes in species structure and composition [63]. Further challenges and reduced mitigation capacity emerge in Boreal forested lands across northeastern Alberta due to oil sand extraction and mining in the Ontario-Québec border. Besides complete habitat removal, these activities result in landscape-scale disturbances due to linear infrastructure, light pollution, and chemical pollution in soils and water bodies, altering biodiversity through complex pathways [64]. While aligning conservation and restoration priorities across forested lands represent a complementary and effective pathway to achieve 30x30 targets, major natural resource projects will likely alter current biodiversity and co-benefits outcomes.

Mining and energy project development are also expected to impact restoration priorities in agricultural lands. In the Prairies, restoration priorities might be impacted by potash mining in Saskatchewan, wind power in Alberta, and electric facilities and transmission lines in Manitoba. Similarly, electric power will represent an immediate pressure for restoration priorities in Ontario's and Quebec's Mixewood Plains. Although mining methods exert varying effects on biodiversity, they generally exacerbate existing pressures in areas that have already lost ecological intactness, such as agricultural lands [65]. Particularly, potash mining's high water use intensity, in combination with climate change, will further impact water availability for an increasing population and growing agricultural production [66]. Energy projects effects are expected to extend beyond habitat removal from in-situ and surrounding linear infrastructure [67]. Wind power can increase bird and bat species mortality [68], resulting in cascading effects on other trophic levels [69]. Run-of-river hydropower alters flow regimes, physical habitats, connectivity, sediment and nutrient dynamics, affecting biodiversity locally as well as upstream and downstream [70]. In some cases (e.g., wind power, hydropower), project impacts in agricultural lands would diminish by coordinating mitigation and restoration actions [71]. Overall, major natural resource projects will increase the baseline of degraded land, leading to an increased challenge in achieving restoration targets.

Conclusions

NbS have the potential to address the intertwined biodiversity, climate, water, and social equality crises. Using an AI-driven framework, we assess this potential by exploring conservation and restoration scenarios to reach Canada's 30x30 biodiversity targets in synergy with climate and water co-benefits. Our results indicate that prioritizing the protection of threatened species and irrecoverable carbon storage, mostly in forested lands, represents a key pathway to conserve 30% of land and improve biodiversity and co-benefits outcomes relative to existing Protected Areas. Restoring 30% of degraded land for effective biodiversity outcomes will require a combination of scenarios: restoring carbon stocks in forest lands and mitigating the effects of reduced ecological intactness and water surface instability in agricultural lands. These findings offer complementary insights for environmental decision-making. On the one hand, implementing holistic frameworks with diverse priority scenarios may reveal strategic conservation and restoration actions that minimize trade-offs and maximize outcomes. On the other hand, targeted land use planning, policies, and investments can strategically maximize biodiversity, climate, and water outcomes.

To accelerate the strategic implementation and investments of holistic NbS, our results outline four key governance recommendations that emphasize multi-dimensional coordination. First, NbS for conservation and restoration actions must be interconnected to guarantee long-term outcomes [72]. Second, conservation and restoration actions should be coordinated across different government levels, asserting Indigenous land governance. Part of this administrative coordination will imply balancing extractive activities against conservation and restoration priorities. The third dimension of coordination involves the public and private sectors. Traditionally, the former relies on policy interventions for conservation, and the latter invests in restoration [33]. Nevertheless, these traditional roles do not have to be static. Finally, decision-making in the digital age requires coordinating scientific, collective, and artificial intelligence [73] through ethical and human-centered frameworks [74]. These transdisciplinary frameworks will require co-developing with regional stakeholders and local rightsholders on which targets, species, co-benefits, interventions, scale, data, and model training are most relevant in their specific contexts.

Study limitations

Despite developing a holistic framework to prioritize conservation and restoration targets, our study has some limitations. First, the complexity of conservation and restoration planning underscores the need for further research at higher resolutions and smaller spatial scales. For instance, high-resolution scenarios could display low-scale conservation priorities in agricultural landscapes that are ruled out in our framework. Aligning species area of habitat maps and land cover changes with habitat quality and connectivity assessments at high resolutions could identify strategic areas for targeted actions[75]. Second, our framework does not directly account for the demand or immediate benefits from biodiversity and related co-benefits. This limitation is illustrated by water surface, which represent the most accessible water source for people[76] but could be complemented by assessing water provision and demand[16]. Similarly, carbon storage co-benefits from NbS in forested or agricultural lands would not necessarily result in interchangeable climate benefits. To address disparate climate benefits, Matthews et al.[52] propose tracking the amount of carbon storage achieved over time and estimating the near-term temperature benefits from that storage. Lastly, while we compare our results with previous work on climate scenarios and assess potential land use conflicts, our prioritization framework does not directly incorporate these assessments. Future prioritization frameworks would benefit from integrating climate and land use scenarios to envision NbS in different shared socio-economic pathways.

Methods

Our study aims to leverage geospatial analysis and Reinforcement Learning to prioritize NbS locations and reach Canada's 30x30 targets while identifying synergies with other co-benefits. To this end, we explored two sets of NbS priority scenarios that maximize the occurrence of threatened vertebrate and plant species within selected land areas. The first set of scenarios focuses on conservation priorities to maximize threatened

biodiversity occurrence and reach 30X30 conservation targets (i.e., conserve 30% of land by 2030) in areas with high ecological intactness (Conservation Scenario 1), high and irrecoverable carbon stocks (Conservation Scenario 2), and stable surface water (Conservation Scenario 3). The other set of priorities is based on maximizing threatened biodiversity occurrence to reach 30X30 restoration targets (i.e., restore 30% of degraded land by 2030) in areas with low ecological intactness (Restoration Scenario 1), carbon stocks losses (Restoration Scenario 2), and significant historical changes in surface water (Restoration Scenario 3). Based on the resulting priority scenarios, we analyze the spatial patterns of conservation and restoration priorities across ecozones and provinces. After, we compare them to current Indigenous-led NbS projects and ongoing and planned major natural resource projects.

Study Area

We use Canada as a case study, which has the second largest country land mass with more than 9.9 million square kilometers [77]. It is estimated that Canada is home to around 80000 species, including mammals, birds, fishes, amphibians, reptiles, plants, and invertebrates [78]. These species are found across diverse ecozones that contain approximately ~25% of global wetlands, boreal forests, and temperate forests [77]. Summing aboveground biomass, belowground biomass, and soil organic carbon, Canada's carbon stocks are estimated at 33.7 PgC, representing 13.7% of global carbon storage, surpassed only by Brazil (18.2%) and Russia (20.9%) [12]. Moreover, Canada has a surface water area of 1.1 million square kilometers, accounting for 26% of the global surface water distribution [76]. Given these ecological and geographic features, Canada presents significant potential to implement NbS initiatives aimed at achieving combined biodiversity, carbon storage, and surface water outcomes.

Canada is also considered to have one of the most extensive areas of global intact ecosystems [79,80]. The current network of Protected Areas covers 12.7% of terrestrial land, partially securing these ecosystems' biodiversity, carbon stocks, and surface water [81]. However, 11.7% of Canada's land area is considered degraded (Department of Economic and Social Affairs - UN, 2019), and 10% of vertebrate and plant species registered by the IUCN red list are classified under some category of extinction risk [83]. Additionally, significant portions of Canada's carbon stocks are at risk of being lost and not recovering by 2050 due to land use and climate change, particularly in ecozones along the Pacific (e.g., Pacific Maritimes), Southern Artic, and Hudson Plains [84]. Surface water faces similar risks, which have resulted in transitions from permanent water cover to seasonal or complete loss [76].

Data processing

To determine NbS priority scenarios of conservation and restoration through Reinforcement Learning, we used a range of datasets on the spatial patterns of biodiversity, carbon stocks, and surface water occurrence in Canada (Table S6). We used the International Union for Conservation of Nature species range polygons to establish the spatial distribution of mammals, fishes, amphibians, reptiles, and plant species in terrestrial ecosystems [83]. Bird species range polygons were obtained from BirdLife International [85]. Among these range maps, we selected species experiencing

some risk of extinction among the IUCN Red List categories: Near Threatened, Vulnerable, Endangered, and Critically Endangered. These selected categories resulted in freshwater fish (n = 24), migratory birds (n = 21), and plants (n = 17) representing 80% of threatened species (n = 77), while the remaining 20% corresponded to mammals (n = 8), reptiles (n = 4), and amphibians (n = 1).

In addition to the distribution of threatened species, we determined ecological intactness at different spatial scales following Soto-Navarro et al.[20] (Table S6). Local ecological intactness was determined through the GLOBIO 4-Mean Species Abundance index that represents the mean abundance of species in a grid cell (~300m) given a particular anthropogenic pressure (e.g., land use, climate change, fragmentation, hunting) and relative to undisturbed areas [86]. This measure of local ecological intactness can be understood as a β diversity measure because it reflects the compositional turnover between disturbed and undisturbed lands [20]. Regional ecological intactness derived from the CSIRO-Biodiversity Habitat Index and provided a measure of habitat transformation impacts on the retention of terrestrial biodiversity [87]. This ~1km resolution index relies on estimating habitat conditions based on land cover and spatial turnover of vascular plant species and reflects the proportion of effective habitat remaining among grid cells with similar species composition before habitat transformation. After resampling to the same resolution (~1km), we estimated the average of both indices to obtain a composite assessment of ecological intactness. The spatial patterns of threatened species and ecological intactness were resampled to a 10km resolution, which corresponded to the size of Planning Units for potential conservation and restoration priority scenarios.

Total carbon stocks were estimated using publicly available biomass and soil organic carbon maps. Biomass was obtained from a 2010 global harmonized map of aboveground and belowground carbon with ~300 m resolution that leverages different vegetation-specific maps (e.g., forest, tundra, grassland, agriculture, tundra) and land cover [88]. Soil organic carbon was obtained from Sothe et al., [11], which produced ~250 m resolution maps at different depths (0-2m) of Canadian terrestrial ecosystems based on soil ground measurements, covariates (e.g., elevation, slope, precipitation, vegetation indices, remote sensing spectral bands) and a random forest algorithm. While this map does not directly correspond to 2010, we assumed the soil carbon estimates approximate that temporal range, considering that the covariates involved represent an average of 20 years (2000-2019). Following Noon et al.[84] and using global peatlands maps [89], we accounted for carbon in peatlands at 1 m depth, which is potentially vulnerable to human activities, and 0.3 m depth elsewhere. After resampling the soil organic carbon maps to the resolution of aboveground and belowground biomass carbon, these estimates were added to determine the stocks of total carbon. Hence, the total carbon estimates we have used here represent the distribution of stocks in 2010 that might be released by subsequent land cover changes.

To determine current total carbon (ca. 2020) and land use emissions, we tracked land cover transitions since 2010. The transitions were determined through annual land cover maps for 2010 and 2020 from the ESA CCI products [90]. We opted for the ESA-

CCI maps due to their involvement in the harmonization process of biomass carbon maps [88]. Using the approach of Hu et al., [91], ESA-CCI land cover classes were translated to 9 IPCC classes to track transitions in land cover and estimate carbon stocks losses or gains for the period 2010-2020. Based on the land cover transitions, the Canadian terrestrial ecozones, and the occurrence of peatlands, carbon stocks changes were estimated separately for biomass carbon and soil organic carbon (Table S7).

Regarding carbon stock losses, ~60% of land cover transitions for the period 2010-2020 involved forests. The transitions from vegetation classes (i.e., forest, wetland, shrubland, grassland, sparse vegetation) to non-vegetation (i.e., urban, bare land) resulted in complete losses of biomass carbon stocks, while partial losses were estimated for transitions involving vegetation classes and agriculture (Table S7). For instance, biomass losses from forest-agriculture transitions were estimated by the difference between the initial biomass carbon in each forest pixel and the terrestrial ecozone average of biomass carbon stocks in agricultural lands. We followed the same approach for similar transitions involving high (e.g., forest) to low-carbon vegetation land cover classes (e.g., shrubland). In the case of soil organic carbon, we assumed that stocks remained stable for transitions involving forests, shrubland, grassland, and sparse vegetation [84,92]. Transitions from vegetation classes to agriculture, urban, and bare land involved a carbon loss function in non-peat soils and complete carbon loss in peat soils [84,93].

Most of the carbon stocks gains involved transitions to forest land cover (~20%). Biomass gains were estimated according to sequestration rates reported in the boreal, temperate lowland, temperate mountain [84], and tundra regions [94]. Gains in soil organic carbon involved transitions from low carbon land covers (i.e., urban, bare land, or agriculture) to vegetation land cover classes (i.e., shrubland, grassland, sparse-vegetation, wetland, forest). Low-high carbon transitions were estimated according to carbon recovery functions reported for temperate and boreal regions, boreal peatlands, temperate peatlands [93], and tundra [95]. We did not assume changes in carbon stocks for land cover transitions involving wetlands and forests, as previous studies suggest that these transitions may not be permanent and are frequently associated with classification errors [96,97]. Based on the changes in biomass and soil organic carbon for the period 2010-2020, both sources of carbon stocks were added to create a total carbon map for 2020. At the same time, the total carbon maps for 2010 and 2020 were used to estimate total carbon stocks changes. All resulting total carbon stocks and total carbon change maps were resampled to a 10km resolution.

In addition to the spatial patterns of threatened species, ecological intactness, and total carbon stocks, we quantified water surface changes. We used the Landsat-derived estimates of changes in global surface water from 1984 to 2015 [76]. This dataset exhibits the spatial and temporal changes of any stretch of open, fresh, and salt water, larger than 30m by 30m. Specifically, we focused on water occurrence change intensity that results from comparing the frequency of monthly water detection between two periods: 1984-1999 and 2000-2015. Thus, the water occurrence change intensity provides a

measure of gains, losses, and persistence. After masking other land covers, we estimated the mean water occurrence change intensity in a 10km resolution across Canada. Capturing these long-term changes in water occurrence may reveal the impacts of climate change and land use while highlighting adaptation actions affecting one of the most accessible sources of water for human populations [76]. Water surface changes were estimated in Google Earth Engine, and the spatial patterns of threatened species, ecological intactness, and total carbon stocks were established using the R package Terra [98].

Reinforcement learning to determine conservation and restoration priorities

We used the Reinforcement Learning algorithm CAPTAIN [27] to identify conservation and restoration priorities to reach 30x30 targets in Canada. The process of identifying priorities in this algorithm can be summarized in four steps: (1) simulate hypothetical spatial training data; (2) train an optimized model of prioritization through Reinforcement Learning; (3) build an empirical environment using observed real-world data; and (4) apply the optimized model within the empirical environment to identify priority conservation and restoration areas (Figure 1).

In the first step, hypothetical natural environments are simulated with a resolution, spatial extent, and several hypothetical species that resemble the empirical environment. Each hypothetical species displays unique spatial distributions, demographic traits, dispersal capacity, and sensitivity to climate and anthropogenic disturbances. Based on the hypothetical environments, we implemented a monitoring policy, a budget (target), and a priority policy to be used for model training. In our case, the monitoring policy gathers information about species (including their presence) and anthropogenic pressures in each planning unit. The budget defines the maximum fraction of planning units that can be prioritized and is a function of the anthropogenic costs. Here, the budget was arbitrarily defined as 10%, that is, a tenth of the total cost of all planning units in the simulated natural environment. Constrained by the budget, the prioritization policy was set to reward the selection of planning units that maximize the occurrence of species and guarantee at least 10% of the spatial distribution of all species while avoiding high costs (e.g., high anthropogenic disturbance).

In the second step (Figure 1), an optimization model was trained to prioritize planning units (i.e., spatial 10X10 km grids) using Reinforcement Learning according to the predetermined monitoring policy, budget, and prioritization policy. To this end, CAPTAIN optimizes the parameters of a neural network to cost-effectively maximize the rewards resulting from prioritizing planning units. As explained in detail by Silvestro et al.[27], this training process relies on a two-phase parallelized evolution strategy that repeats in several epochs. During the first phase, changes in policy parameters are randomly perturbed and tested in a simulated change in the environment (i.e., species distributions and anthropogenic pressures), resulting in priority actions and a reward. After simulating these changes in different iterations that occur in parallel, the second phase aggregates the results of these iterations to identify improvements in the rewards and update the neural network parameters. The two-phase process repeats across different epochs (here, 100), and the rewards from a current epoch are compared with

the weighted average results of previous epochs in a process defined as an advantage function. Thus, based on the simulated natural environments, we produced a trained optimization model capable of cost-effectively identifying priority planning units that maximize the occurrence of species.

In the third step, we integrated observed spatial datasets for Canada as an empirical environment. This environment was created by dividing the country's land surface into planning units of 10X10 km that included information regarding the presence of threatened species, the occurrence of Protected Areas, composite ecological intactness, total carbon stocks, total carbon stocks changes, and water occurrence change intensity. Using the Canadian Protected and Conserved Areas database [81], we excluded planning units with a Protected Area surface equal to or higher than 50 km2, resulting in 12.25% of the area assumed to be already protected and therefore excluded from priority scenarios. Estimates regarding ecological intactness, carbon stocks and water occurrence change intensity across planning units were normalized to create a scale of costs for conservation and restoration priority scenarios.

In the final step, the priority scenarios for conservation and restoration aimed to reach 30X30 targets that would maximize the occurrence of threatened biodiversity, guaranteeing at least 10% of all species ranges while avoiding specific costs. We aimed to reach 30x30 targets for the conservation scenarios by identifying at least ~16200 priority planning units (~17.75% of the total area). In Conservation Scenario 1, the normalized ecological intactness values were recalculated so that the highest value (~ 1), and therefore the highest cost, corresponded to the lowest ecological intactness. This cost scale resulted in rewarding the selection of planning units displaying low cost-high ecological intactness (~0). Similarly, the Conservation Scenario 2 was based on a cost scale that rewarded the selection of low cost-high total carbon. To prioritize carbon stocks that, if lost, would not recover by 2050 [84], the original cost of planning units found in areas with irrecoverable carbon stocks was further reduced to a tenth of the original value. Using a cost scale displaying the largest values for the most intense water occurrence changes, the Conservation Scenario 3 rewarded the prioritization of planning units displaying low cost-low water surface change. Consequently, the conservation scenarios prioritized ecological intactness, climate change mitigation potential, and surface water stability, suggesting proactive NbS with low to moderate anthropogenic pressures.

Following the removal of conservation priorities from the empirical environment, we performed the restoration scenarios. The three scenarios aimed to identify priorities areas to restore 30% of degraded land in 2019, which corresponded to 3.5% of the total land area (~3300 planning units) [82]. While the restoration scenarios had the same themes as the conservation scenarios, we used a different scale of costs and rewards for the prioritization process. Restoration Scenario 1 and Scenario 3 were based on scales of costs that rewarded the prioritization of planning units with low intactness and high-water occurrence change intensity, respectively. Using a normalized scale where values closer to zero represented the largest carbon stock losses, the Restoration Scenario 2 rewarded the prioritization of areas that have experienced carbon stocks

losses over the period 2010-2020. Similar to the Conservation Scenario 2, the cost of carbon stocks losses in planning units with irrecoverable carbon stocks (i.e., irrecoverable by 2050 via natural processes) was reduced to a tenth of the original value. By prioritizing reduced ecological intactness, carbon stock losses, and surface water instability, the restoration scenarios produced priority areas for reactive NbS requiring active management and adaptation actions under high anthropogenic pressures.

Conservation and Restoration priorities relative to Indigenous-led NbS

We identified spatial alignments between conservation and restoration priorities with Indigenous Lands, including Indigenous-led NbS funded by the federal government of Canada. We focused on two indigenous-led NbS: government-recognized Indigenous Protected Conserved Areas (IPCAs) and the Indigenous Guardians Federal Program. IPCAs are part of Indigenous-Led Area-Based Conservation programs [99]. Based on the Canadian Protected and Conserved Areas Database [81], three IPCAs were included: Edéhzhíe Protected Area, Thaidene Nëné Territorial Protected Area, and Ts'udé Nilı̨né Tuyeta Territorial Protected Area. The Indigenous Guardians Federal program funded projects from 2018-2022 (Government of Canada, 2023), aiming to support monitoring, stewardship, and conservation actions across traditional lands and waters [101]. Using the public database of Indigenous Guardians funded initiatives [100], we related proponents, such as Indigenous governments, to Indigenous Lands' legislative boundaries [102]. When these boundaries did not relate to an Indigenous Guardians project, we defined them as Indigenous Lands. After, for each conservation and restoration priority planning unit, we identified the nearest distance to an Indigenous-led NbS or other Indigenous Land centroid location, using the function nearest in the R package Terra [98]. The conservation and restoration priorities' distance to Indigenous-led NbS and Indigenous Lands allowed us to identify local opportunities for equitable NbS.

Conservation and Restoration priorities relative to major natural resource projects

Finally, we compared the spatial distribution of resulting conservation and restoration priorities with major natural resource projects in Canada. The Major Projects Inventory provided the location of forestry, mining, and energy sector projects currently under construction or planned within the next ten years [103]. This inventory included high-impact projects with a minimum investment between 20 (forestry and electricity) and 50 million (mining and energy) CAD. In addition to extractive activities, energy sector projects (i.e., solar, hydro, and oil), displayed diverse infrastructure facilities for processing and transportation. Similar to Indigenous-led NbS and other Indigenous Lands, we identified the nearest distance of each conservation and restoration priority to major natural resource projects in each sector. By analyzing this spatial distribution, we aimed to identify potential land conflicts of conservation and restoration actions with the extraction of natural resources.

Resource availability

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Camilo Alejo (camilo.alejo.monroy@futureearth.org).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data and code that support the findings of this study are openly available in the Open Science Framework at https://osf.io/k7wjq/

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Author Contributions

Conceptualization, C.A., A.L., H.D.M.; Methodology, C.A., H.D.M., Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, Project Administration C.A.; Writing – Review & Editing, C.A., H.D.M., A.L., A.V.; Supervision, H.D.M.; Funding Acquisition H.D.M., A.L.

Declaration of interests

The authors declare no competing interests.

Supplemental Information

Document S1. **Figure S1.** The land surface extent of Protected Areas in Canada. A. Area distribution across Canadian Terrestrial Ecozones. **Figure S2.** The distribution of threatened vertebrate and plant species in Canada. **Figure S3.** The distribution of Conservation and Restoration Priority Scenarios across Canadian Terrestrial Ecozones. **Table S1.** Summary statistics of ecological intactness, carbon storage, and water occurrence change intensity in Canadian Terrestrial Ecozones. **Table S2.** Summary statistics of threatened species, species richness, ecological intactness, carbon storage, and absolute water occurrence change intensity in Protected Areas and Conservation Priority Scenarios across Canadian Terrestrial Ecozones. **Table S3.** Summary statistics

of threatened species, species richness, ecological intactness, carbon storage, and absolute water occurrence change intensity in Protected Areas and Conservation Priority Scenarios across Canadian Terrestrial Ecozones. **Table S4.** Conservation and restoration priorities overlaps with Indigenous-led NbS and Indigenous Lands. **Table S5.** Conservation and restoration priorities overlaps with major development projects. **Table S6.** Datasets used to determine and analyze Conservation and Restoration priority scenarios. **Table S7.** Biomass and soil organic carbon change estimates from land cover transitions.

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