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RESEARCH ARTICLE

Carbon stock protection and food production are key targets for conservation planning in a landscape of public and private lands

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Abstract
Context Demand for land for urban development, food production, and protected areas is increasing, leading to land scarcity. In response, agricultural lands are increasingly targeted for protection. Yet, which land attributes should be used to identify priority lands to protect remains largely unknown.
Objectives (1) Is private land protection necessary to protect nature's contributions to people [NCP] in a region dominated by public protected areas? (2) Which NCP indicators are the most important drivers of optimal land protection?
Methods We applied the NCP framework in Idaho's Snake River Plain, a water-limited, climate-sensitive ecoregion dominated by public lands with a quickly growing human population. We quantified 21 NCPs and used systematic conservation planning to generate cost-efficient land protection solutions. We also developed a sensitivity analysis workflow to determine which NCP inputs were most influential for priority protected area selection.
Results Current protected areas were highly effective; for 17 of the 21 NCP, the majority of each NCP (> 50% of its total) was covered by public and protected private lands. However, food production is severely under-protected. Food production and carbon stock protection had the most influence on conservation planning scenarios. Ignoring climate-related NCP in agricultural land protection decisions, even in sub-regional planning where climate seems relatively homogenous, can limit contributions to climate mitigation and adaptation.
Conclusions Private land protections complement public lands networks for NCP protection. Climate considerations are important to include even in local scale conservation planning. Our reproducible workflows for NCP quantification and conservation planning sensitivity analysis can be used to systematically plan for a broad suite of human benefits.

Keywords Systematic conservation planning · Nature's contributions to people · Private land conservation · Sensitivity analysis

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Introduction

Land is a limited resource, and globally, humanity is playing a balancing act among three essential land uses. Highly developed urban areas can provide safe

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and affordable housing (United Nations Sustainable Development Goal 11, Thacker et al. 2019), agricultural areas produce food (UN SDG 2), and protected areas provide diverse benefits, including terrestrial habitat (UN SDG 15), climate change mitigation (UN SDG 13), and sustainable tourism (UN SDG 8, Kettunen et al. 2021). The interplay between urban, agriculture, and protected lands is well documented. Built-up areas currently cover very little of the Earth's surface (ca. 2%), but they are projected to double in area by 2040 (van Vliet et al. 2017). Over half of urban expansion is predicted to occur on agricultural lands that currently grow food crops or animal feed crops (van Vliet et al. 2017). Urban expansion onto croplands is accompanied by agricultural land expansion into new areas and intensified use of remaining agricultural lands (You 2016; van Vliet 2019). Agricultural lands already cover ca. 50% of global ice-free lands (Ellis et al. 2010), and are predicted to increase 10–25% by 2050 (Schmitz et al. 2014). Rapid growth of urban and agricultural lands have been accompanied by the expansion of protected area networks, from ca. 10% of Earth's lands in 1990 to ca. 17% of terrestrial areas in 2020 (UNEP-WCMC and IUCN, 2021), and there are calls to protect up to 50% of the Earth (Dinerstein et al. 2020). With a limited amount of land on Earth, meeting the growing needs for food, developed land, and nature conservation is a major challenge for humanity.

One way to resolve increasing conflicts is to expand the public protected area network to include private lands. Within protected areas, the goal is often to protect ecosystems, biodiversity, and the regulating contributions they provide by restricting intensive human use (Dudley et al. 2010), yet private lands may be more suited to meeting these goals than current protected areas. Relatively isolated areas with high tourism attractiveness are overrepresented in the global protected area network (Baldi et al. 2017), while highly productive lands with access to water and fertile soil are more likely to be privately owned (Norton 2000; Robinson et al. 2019). Private lands contain more threatened species and ecosystems than public lands (Graves et al. 2019), with some species and ecological communities existing solely on private lands (Ivanova and Cook 2020). Yet despite private lands' importance for humans and biodiversity, more land use restrictions, such as limits on development or food production, are in place on public lands (Dietz et al. 2023). Thus, food supplies arise largely from private lands managed for agriculture. There has been growing interest in expanding the private protected lands network via protected agricultural lands [PALs] (Freedgood et al. 2020), whose primary goal is to protect farmland and ranchland from further development. Depending on management goals, PALs promote continued food production, rural community well-being and character, and increased biodiversity (Brabec and Smith 2002; Robinson et al. 2019). As states and localities invest limited resources in implementing new PALs, they will want to identify which private lands provide the most benefits for the least cost to maximize their investment, but there is no systematic way to identify priority PALs.

The framework of nature's contributions to people [NCP], defined as "all the contributions, both positive and negative, of living nature to quality of life for people" (Díaz et al. 2018), is a useful tool to measure the various benefits land can provide (Bruley et al. 2021). NCP formalizes important conceptual advances in its antecedent ecosystem services, such as recognition of and respect for diverse worldviews, non-instrumental valuation (i.e. pluralistic, non-material, non-biophysical valuation), and the distinction of generalizing and context-specific perspectives (i.e. the distinction between universally applicable categories and resistance to universally applicable schemas, Kadykalo et al. 2019). Some current programs to establish PALs use NCP such as soil quality, farmland quality or certain unique attributes (e.g. provision of valued rural amenities like processing facilities or recreational opportunities), or wildlife habitat (Hellerstein et al. 2002; Miller 2015), as ranking criteria to decide which lands to invest in. However, many other NCP are often not considered when identifying new PALs. Of particular relevance is land's suitability for climate change mitigation and adaptation. Rising temperatures, decreasing water availability, and more frequent droughts and other natural disasters, can be equally or more detrimental to natural and agricultural lands than human population impacts and the expansion of built-up lands (Requena-Mullor et al. 2023). However, climate-related NCP, such as carbon [C] storage, the facilitation of species migration, and climate refugia, are rarely considered in the identification of new PALs.

Incorporation of NCP into PALs planning would enable practitioners to identify areas where PALs could provide the most benefits to humans and nature. Systematic conservation planning [SCP] is a proactive framework used in protected area design that quantifies conservation values and identifies protected areas efficiently, to meet conservation goals by maximizing the ratio of benefits to cost (Kukkala and Moilanen 2013; Beyer et al. 2016). SCP has been used to prioritize lands that protect biodiversity (e.g. González-Fernández et al. 2022), and have also incorporated other NCP, frequently C storage and water provision, to prioritize protections within public–private lands networks (e.g. Williams et al. 2020). However, planning for conservation involves different goals than planning for PALs. Despite previous literature indicating that changes to land selection priorities result in different protection strategies (Williams et al. 2020; de Assis Barros et al. 2022), there is limited understanding of how key factors impact the selection of PALs. The existing body of SCP research may provide an excellent framework for prioritizing PALs, but to our knowledge, it has had limited implementation (i.e. Halperin et al. 2024).

The overarching goal of this study is to develop a framework for systematically identifying priority lands for inclusion in a protected area network that includes both public and private lands. We conducted our study in the Snake River Plain of Idaho, of which 58% is public protected lands, and also contains high quality cropland of global importance (Idaho State Department of Agriculture, n.d.). The region is also experiencing one of the highest population growth rates of any state in the United States (United States Census Bureau, 2021a) and because public lands present some barriers to conversion (see Table A1), urban development occurs preferentially on the highest quality agricultural lands (Freedgood et al. 2020; Halperin et al. 2023). There is a strong push to protect privately-owned agricultural lands from development, but it is uncertain whether more protected lands are necessary, nor how to prioritize which private lands should be protected. In this study, we measured a diverse suite of NCP in this region across public and private land tenures, and then we used SCP to produce maps of cost-efficient priority lands that optimize NCP protection. We additionally developed a systematic sensitivity analysis workflow that guides the inclusion of input datasets. Our specific research questions were:

Is private land protection necessary to protect NCP in a region dominated by public protected areas?
Which NCP indicators are the most important drivers of optimal land protection?

Methods

Study area

The Snake River Plain ecoregion of the United States (U.S. Environmental Protection Agency 2013) intersects with 26 Idaho counties (109,700 km^2). It contains productive croplands (Freedgood et al. 2020), localized yet rapidly growing highly developed urban areas (United States Census Bureau, 2021b), and public rangelands grazed by livestock (Fig. 1a). This region features two primary ecological zones, the river plain and the shrub steppe, and a diverse range of social systems, from urban and exurban systems to dryland agriculture and rural public lands, that together form a diverse array of social-ecological systems (Aho et al. 2022). A majority (58.1%) of lands in the Snake River Plain are federally owned. About one third of the region (33.9%) is privately owned, of which a small percentage (0.4%) are PALs or other easements (Fig. 1b). We excluded tribal lands (2,628 km^2, 2.4% of the study area) from this analysis because they have complex land management and protection systems, where the assumption that the cost of land protection scales with fair market value is not applicable (Middeton 2011). The remaining land tenure categories have different levels of protection that affect NCP persistence (Online Resource A.2).

Data

Land use

We primarily used Farms Under Threat 2040 land use data (Conservation Science Partners (CSP), 2020; Hunter et al. 2022), which contain agriculture-specific land classes (e.g. cropland, rangeland). They also differentiate lands within low-density residential areas, which we hypothesized would have different NCP than the same types of land cover outside of residential areas (not shown

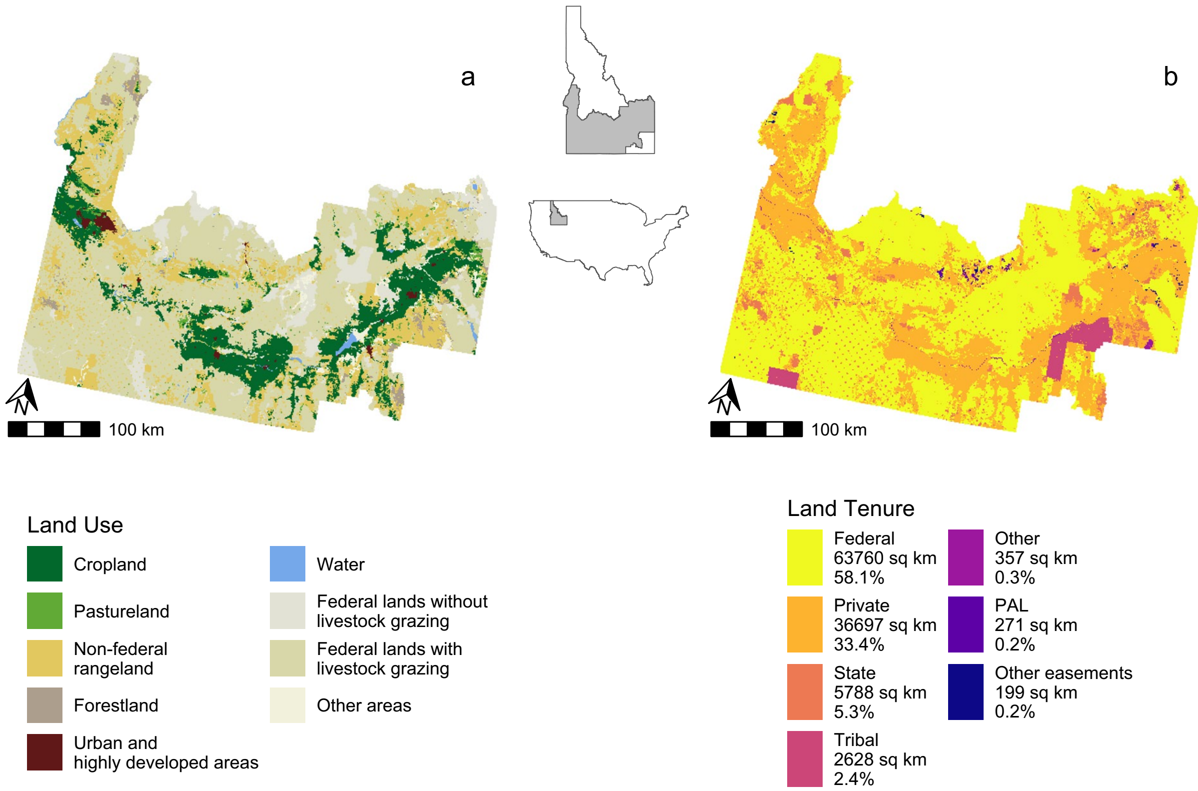

Fig. 1 Land use (Hunter et al. 2022) and land tenure (see Table A1) in Idaho's Snake River Plain

in Fig. 1, see Online Resource B.1). This dataset allowed us to use agriculturally relevant yet generalized land classes for our NCP models for which we could assign relevant NCP estimates. We also implemented the National Land Cover Database (Dewitz and U.S. Geological Survey, 2021) and the Cropland Data Layer (USDA NASS 2020) in models where NCP estimates were available and aligned with these data (see Online Resource B.1 and B.2.2).

NCP data and models

We used six NCP categories: carbon [C] stock protection, climate adaptation, food and feed production, habitat quality, water quality, and nature-based recreation probability (Table 1, Fig. A1) that span a range of heavily co-produced with humans (e.g. food and feed) to heavily nature-produced (e.g. habitat creation).

Land cost

We used a spatial dataset of estimated land values (million USD/km2; Fig. B7) calculated across the contiguous United States, which represents the cost of purchasing lands outright (Nolte 2020; Halperin et al. 2024). We assume easement costs will scale with land value so that more expensive parcels will be more expensive easements.

We upscaled each continuous spatial dataset to 1km resolution, chosen as representative of the average size of an agricultural easement based on the mean easement size in the Protected Agricultural Lands Database (0.7 km^2, Table A2). All analyses were performed using R Statistical Software (v4.3.3, R Core Team 2024).

Table 1 NCP models and data used as inputs for the systematic sensitivity analysis workflow

NCP Indicator	NCP Category	Description	Citation	Methodology
C Storage	C stock protection	Regional estimates of C storage using the InVEST Carbon Storage model	Halperin et al. (2023); Sharp et al. (2020)	Online Resource B.2.1.1, Figure B1a
C Storage	C stock protection	Global, remote sensing-based estimates of C storage in biomass	Spawn and Gibbs (2020)	Online Resource B.2.1.1, Figure B1b
Soil Organic C	C stock protection	Global interpolation of soil organic C stock measurements	Hengl and Wheeler (2018)	Online Resource B.2.1.1, Figure B1c
Climate Accessibility	Climate Adaptation	The degree to which current climate conditions will be locally accessible in the future. Areas with higher climate accessibility will support species' movement to suitable climates	Suraci et al. (2023); Hamann et al. (2015)	Online Resource B.2.1.2, Figure B2a
Climate Stability	Climate Adaptation	The similarity between present and future climate. Areas with higher climate stability may serve as climate refugia	Suraci et al. (2023); Carroll (2018)	Online Resource B.2.1.2, Figure B2b
Crop Provision	Food and Feed	Estimates of crop yields (tons, 5-yr period)	Halperin et al. (2023)	Online Resource B.2.2, Figure B3a
Livestock Feed Provision	Food and Feed	Estimates of feed crops and livestock forage (animal unit months, 5-yr period)	Halperin et al. (2023)	Online Resource B.2.2, Figure B3b
Crop Value	Food and Feed	Prices received for crops over five years	USDA NASS (2021)	Online Resource B.2.2, Figure B3c
Agricultural Potential	Food and Feed	The Productivity, Versatility, Resiliency (PVR) metric is a measure of land quality based on its ability to support high yields and a variety of crops now and continuing into the future	Freedgood et al. (2020); Conservation Science Partners (CSP) (2020)	Online Resource B.2.2, Figure B3d
Nitrogen Retention Capacity	Water Quality	Estimated percentage of nitrogen inputs that each watershed retains using the InVEST Nutrient Delivery Ratio model	Chaplin-Kramer et al. (2019); Halperin et al. (2023); Sharp et al. (2020)	Online Resource B.2.3, Figure B4a
Estimated Nitrates	Water Quality	Nutrient contamination "rank" from modeled nitrate levels, where the cleanest lands have the highest rank	Ransom et al. (2021)	Online Resource B.2.3, Figure B4b
Landscape Condition	Habitat	Large intact natural areas or corridor zones between them	Idaho Department of Fish and Game (2013)	Online Resource B.2.4, Figure B5a
Ecological Connectivity	Habitat	The ability of a landscape to support organism movement and link habitats	Suraci et al. (2023)	Online Resource B.2.4, Figure B5b

Table 1 (continued)

NCP Indicator	NCP Category	Description	Citation	Methodology
Habitat Quality	Habitat	Spatial variation of habitat quality, which is lowered by the presence of and proximity to habitat threats, using the InVEST Habitat Quality model	Halperin et al. (2023); Sharp et al. (2020)	Online Resource B.2.4, Figure B5c
Ecological Integrity	Habitat	The degree to which a location remains in its natural state without human influence	Suraci et al. (2023)	Online Resource B.2.4, Figure B5d
Terrestrial Species of Concern	Habitat	Presence of federally listed species and overall species richness	Idaho Department of Fish and Game (2013)	Online Resource B.2.4, Figure B5e
Biodiversity Value	Habitat	Sites that support biotic assembleges characteristic of the geophysical setting	Anderson et al. (2023)	Online Resource B.2.4, Figure B5f
Terrestrial Resilience	Habitat	Sites with high diversity of topoclimates accessible to species	Anderson et al. (2023)	Online Resource B.2.4, Figure B5g
Wetland / Riparian	Habitat	Important wetland/riparian habitats	Idaho Department of Fish and Game (2013)	Online Resource B.2.4, Figure B5h
Recreation Probability	Recreation	Global-scale recreation probability model ensemble	Hooftman (2023)	Online Resource B.2.5, Figure B6a
Recreation Probability	Recreation	Regional-scale recreation model for the probability of nature-based recreation opportunities	Halperin et al. (2023)	Online Resource B.2.5, Figure B6b, Table B3

The methods column lists the sections in the Online Resource B with more information about data sources and processing for each NCP dataset.

Analytical approach

Question 1: Is private land protection necessary to protect NCP in regions dominated by public protected areas?

We calculated the percent of each NCP indicator provided by each land tenure category. We compared the percent NCP provided to the percent of the land tenure category within the study area to quantify which land tenure categories are contributing more or less NCP than expected. For example, if a land tenure category covers 30% of the study area and contributes 30% of total recreation NCP, it is providing its expected share of NCP.

Question 2: Which NCP indicators are the most important drivers of optimal land protection?

We generated multiple series of systematic conservation planning [SCP] scenarios that use a set of NCP indicators to generate a solution containing priority protection areas. We used the prioritizr R package with a Gurobi solver in R (v8.0.3, Hanson et al. 2024; v12.0–0, Gurobi Optimization, LLC, 2024). SCP in prioritizr requires, at minimum: (1) an objective function, (2) conservation features to protect, (3) cost of protection, and (4) protection targets (> 0% and < 100% of each conservation feature).

We used the minimum set objective function for this analysis, which generates priority areas that acheive conservation targets for each feature at the lowest possible cost. To test sensitivity to features across targets, we used a range of protection targets from 5 to 75%, incremented by 5%, of each NCP indicator. We also chose 30% as a specific target to examine following global conservation initiatives (Convention on Biological Diversity, 2022).

For conservation features, we used the NCP indicators described above. Besides a few highly correlated indicators (the two carbon models, crop provision-crop value, and habitat quality-ecological integrity; Fig. C1), most NCP were less correlated on a pixel-to-pixel basis. However, reaching protection targets for one indicator can still result in protecting others implicitly. To better understand the main drivers among and uniqueness of the NCP features, we implemented a novel sensitivity analysis to reduce the number of NCP indicators in our SCP scenarios (see Online Resource 2.3.3 and the workflow diagram Fig. A1).

Selecting features: systematic sensitivity analysis workflow

To reduce NCP indicators in the all-NCP scenario, we ran a series of SCP scenarios in each NCP category. We set NCP protection targets to range from 5 to 75%, incremented by 5%, created SCP scenarios for each possible combination of indicators, and calculated a priority areas network for each scenario at each target. We also created a full solution for each category that contained all its NCP indicators. We then quantified the spatial dissimilarity between each solution and the full solution for that NCP category and target using Earth Mover's Distance [EMD]. EMD is a spatial similarity measure that supposes each pixel value in raster A is a pile of earth and each pixel value in raster B is a hole. It calculates the effort (distance times amount of earth) need to fill all the "holes" in raster B with the earth in raster A (Roura-Pascual et al. 2010). A lower EMD indicates that a pair of rasters have a more similar spatial distribution. To assess dissimilarity across targets, we plotted the EMD of each solution at each target and calculated the area under the EMD curve [AUC-EMD] (Online Resource C). Solutions with the lowest AUC-EMD are more similar to the full solution across all targets. For all EMD calculations, we aggregated solutions to 5km as the algorithm could not handle larger matrices, and normalized all solutions so they summed to one. All EMD calculations were performed with the emdist R package (v0.3–3, Urbanek and Rubner 2023).

When selecting NCP indicators in each NCP category, we determined that redundant indicators were present if there were solutions with AUC-EMD < 1000, a threshold based on visual examination of AUC-EMD plots (Fig. C2 – C7 and Table C1). If there were solutions with < 1000 AUC-EMD, we selected the solution with the lowest AUC-EMD and fewest number of included indicators. The NCP indicators not used in the selected scenario were classified as redundant.

Influential NCP

To identify the most influential NCP in our solution, we performed a similar sensitivity analysis to the workflow described above. We compared scenarios that left out one NCP indicator or one entire NCP category to the solution with all indicators and categories (the all-NCP solution). We determined the most influential NCP indicators and categories by identifying the "leave one out" scenarios with the highest AUC-EMD values.

Results

Is private land protection necessary to protect NCP in regions dominated by public protected areas?

Over 55% of most NCP in the study area were provided by federal lands, with the exception of food and feed NCP, of which only 12.2% were provided by federal lands (Fig. 2, see Figure D1 for all 21 NCP datasets). Over 80% of food and feed NCP were contributed by private lands, but private lands contributed less of all other NCP than expected, with the exception of wetland/riparian habitat. State lands, PALs, and other easements contributed NCP fairly equivalent to their land cover extent.

Selecting features: systematic sensitivity analysis workflow

For the climate adaptation and recreation NCP categories, removal of any single indicator resulted in a solution very different from the full solution. For these NCP categories, we retained all indicators. For the other NCP categories, removal of one or more indicators resulted in solutions very similar to the full solution (Fig. 3). This subset of indicators (listed in Fig. 3) were classified as redundant and removed from the all-NCP scenario. Without the redundant indicators, the all-NCP scenario included two C stock protection indicators (soil organic C and InVEST C storage), two climate adaptation indicators (climate accessibility and climate stability), three food and feed indicators (crop provision, livestock feed provision, and agricultural potential), one water quality indicator (N retention capacity), four habitat indicators (wetland/riparian, ecological connectivity, terrestrial resilience, and habitat quality), and two recreation indicators (both recreation probability models).

Which NCP indicators are the most important drivers of optimal land protection?

The all-NCP solution was most sensitive to two NCP categories: (a) food and feed, especially agricultural potential, and (b) C stock protection, especially soil

Fig. 2 Summarized percent of each NCP category provided by each land tenure category. Deviation from expected measures a land tenure category's contributions relative to their size. If a category covers 30% of the study area and contributes 30% of total recreation NCP, the deviation from expected is 0. Percent of land area for each land tenure category is slightly higher than those in Fig. 1 because the study area and NCP indicators were modified to exclude tribal lands

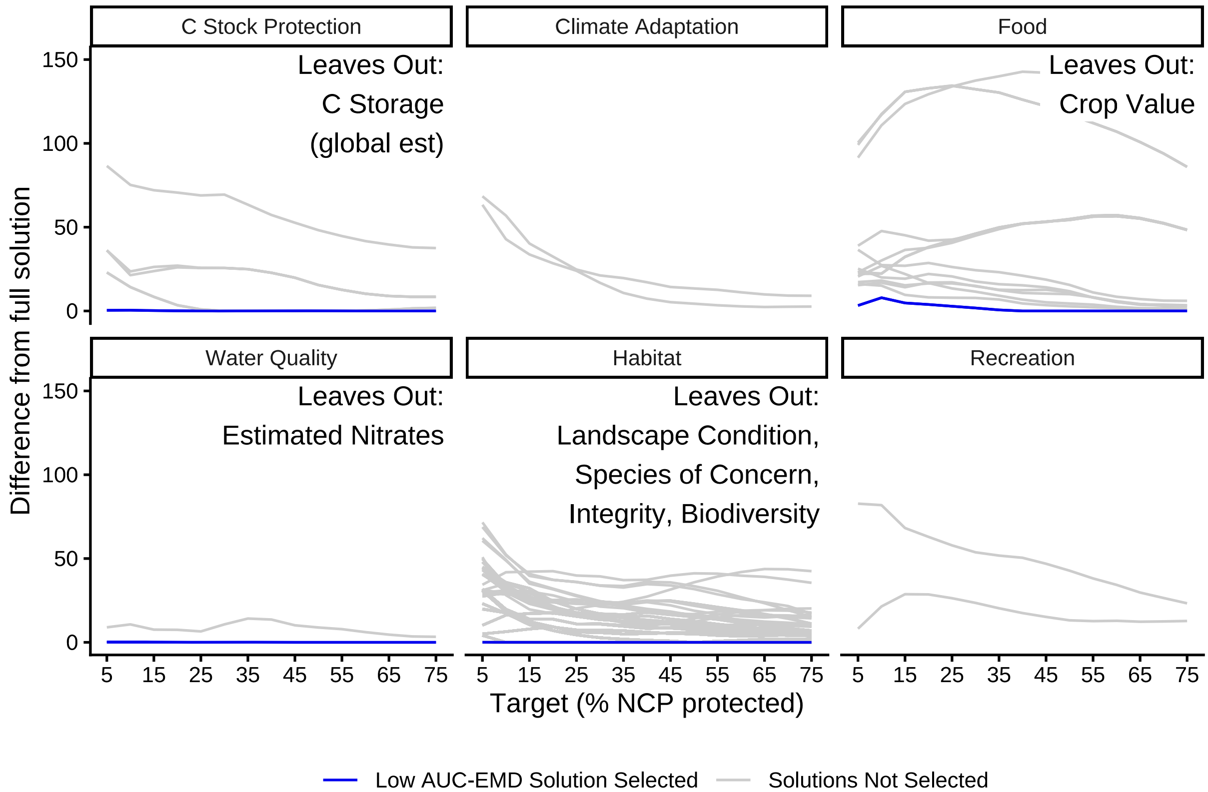

Fig. 3 Results of the sensitivity analysis to identify redundant NCP datasets. For each NCP category, we created a full solution containing all indicators in that category (Table 1) and alternate scenarios with every possible combination of NCP indicators within each category. We then tested the spatial difference (EMD) between the alternate solutions and the full solution. Removal of NCP indicators in some NCP categories had a minute effect on priority area solutions. Solutions that were very similar to the full solution but did not contain all indicators are depicted in blue, with the NCP indicators they omitted noted. We classified these omitted indicators as redundant and did not include them in the all-NCP analysis. Other solutions tested are depicted in gray

organic carbon (Fig. 4). The all-NCP solution was highly sensitive to inputs when NCP protection targets were lower and less sensitive at higher NCP protection targets, but this relationship was nonlinear. The target chosen affected the sensitivity of the solution to different indicators. For example, the solution was more sensitive to the climate adaptation indicators than the food and feed indicators at targets 5–10%, but was more sensitive to the food and feed indicators than the climate adaptation indicators at targets 15–75% (Fig. 4).

Since the all-NCP solution was most sensitive to food and C stock protection NCP, we compared the outcomes of these dissimilar solutions when these NCP were left out (Figs. 5, 6, Table D1). The all-NCP solution (Fig. 5a) was 33,677 km^2, while the Leave Out (LO) Food solution (Fig. 5b) was 34,244 km^2 and the LO-C stock protection solution (Fig. 6b) was 33,517 km^2.

The all-NCP and LO-C stock solutions were composed of ca. 9% cropland, with similar crop types present (Fig. 6d-e, Table D1), while the LO-food solution was only 0.7% cropland, which was mainly alfalfa-growing (Fig. 5d-e, Table D1). The all-NCP solution had slightly lower inclusion of rangelands and slightly higher inclusion of forestlands than the LO-C stock solution (Fig. 6d, Table D1).

The all-NCP and LO-C stock solutions were composed of less federal lands (59.1% and 58.8%, respectively) than the no-food solution (74.7%, Table D1). Unprotected private lands were included in all solutions, but were especially present in solutions that protect food NCP.

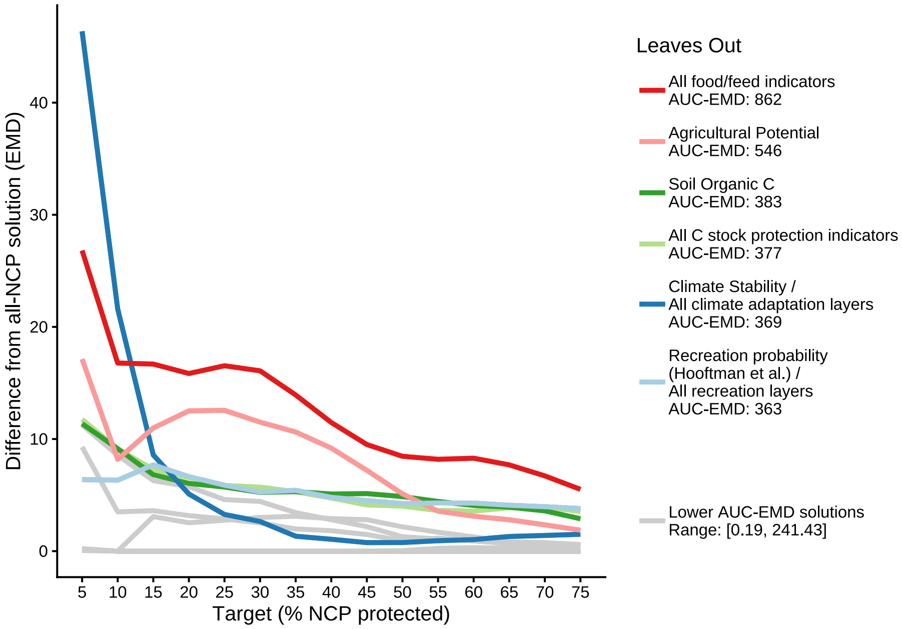

Fig. 4 Sensitivity of the solution as a function of target protection, measured by Earth Mover's Distance, a spatial similarity measure. The six solutions with the highest area under the Earth Mover's Distance curve [AUC-EMD] are the most influential, and are depicted with colored lines. The legend reports the area under the EMD curve values for these scenarios and the inputs that these scenarios omit. The lower-sensitivity NCP categories are shown in gray

The total fair market value of lands in the LO-food solution ($7.48B) was 22% less than the all-NCP solution ($9.64B), while the total value of lands in the LO-C stock solution ($9.43B) was only 2% less than the all-NCP solution. Food is included as a target NCP in establishing PALs, so these extra costs are accepted implicitly, but the addition of climate goals would result in relatively little extra investment from institutions.

When NCP were removed from scenarios, less of those NCP were protected, but the extent of protection was variable. In the LO-food solution, food and feed NCP were 27–97% less protected (Fig. 5), while in the LO-C stock protection solution, C stock protection NCP were 1–9% less protected.

Discussion

Is private land protection necessary to protect NCP in a region dominated by public protected areas?

Federal lands provided a wide variety of NCP, often exceeding their expected provision. In the public-lands dominated landscape of Idaho's Snake River Plain, they play an important role in providing NCP overall. However, private lands provided the most food and feed NCP, which is consistent with other studies showing that private land protections are critical to protect the full suite of NCP that humans value (Ivanova and Cook 2020; Chapman et al. 2023). In Idaho specifically, the food NCP provided predominantly by private lands and the recreation NCP provided by public lands are important elements of rural economies and identities (Winkler et al. 2007). Networks that include both public and private lands have the highest chance of providing the widest range of NCP.

This research adds to the debate on where protected areas should be established and what should occur in those areas (Holmes et al. 2017; Dinerstein et al. 2020). The International Union for Conservation of Nature (IUCN) defines protected areas as spaces that are managed "to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (UNEP-WCMC 2019). The IUCN definition encompasses a range of land uses from strict human-exclusion reserves to areas with limited extractive use, yet does not explicitly include areas of cultural importance (Dudley et al. 2010). This definition seemingly excludes PALs, yet PALs can provide a suite of NCP and support rural social services and culture. Though food production NCP and other NCP may not always co-occur in the same space (Halperin et al. 2023), PALs can protect multifunctional agricultural landscapes that do provide

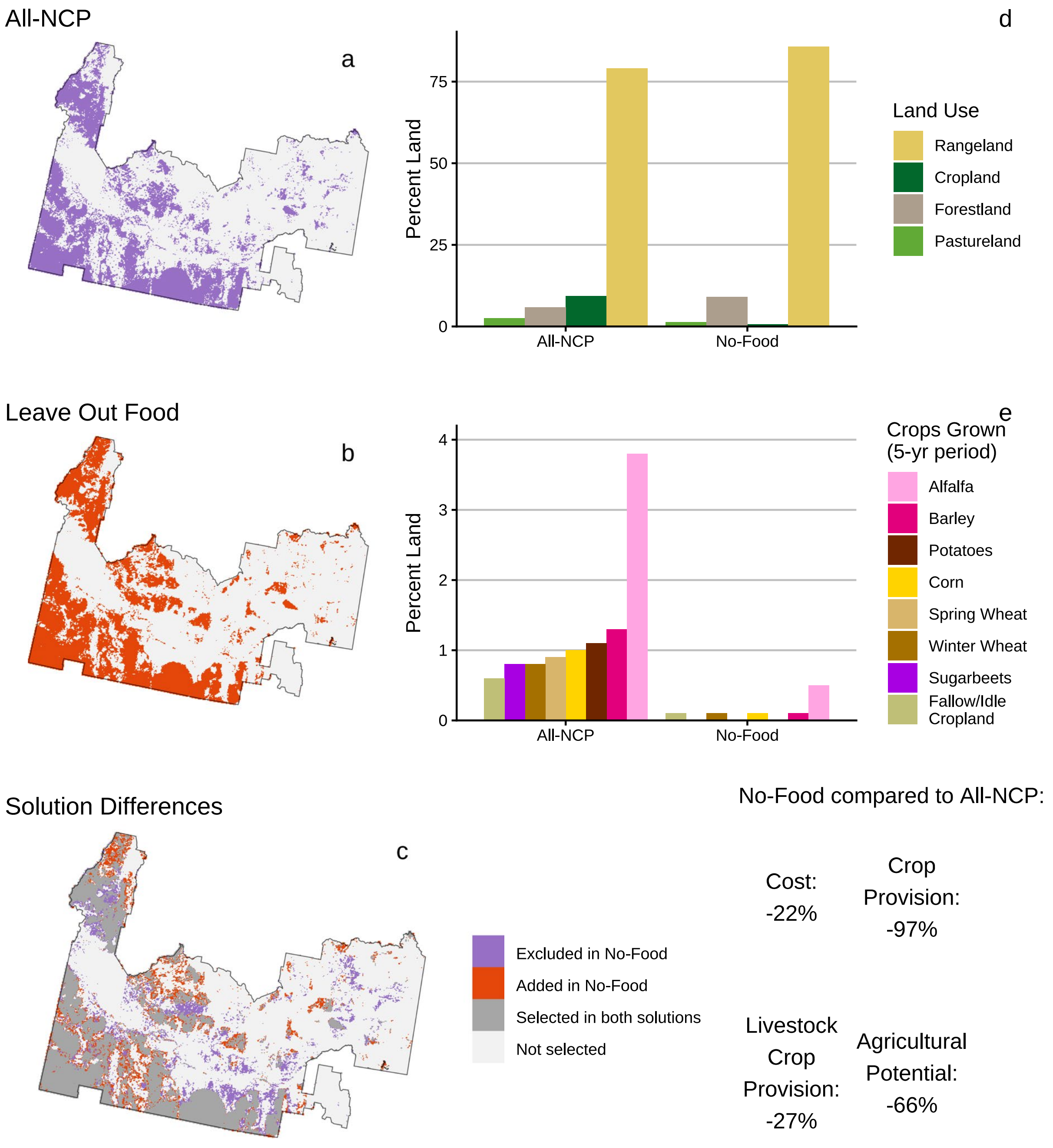

Fig. 5 Differences between the all-NCP solution and the Leave Out Food (No-Food) solution at 30% targets. **a** The All-NCP scenario includes the 14 NCP indicators selected in our sensitivity analysis. **b** The Leave Out Food (No-Food) scenario includes 11 NCP indicators, excluding the 3 selected food indicators. **c** The No-Food solution excludes many lands included in the all-NCP solution and includes some lands that were not chosen in the all-NCP solution. Each solution has different compositions of **d** land use, **e** crops grown in a 5-yr period, cost, and NCP protected. See Online Resource D.2 for more detail.

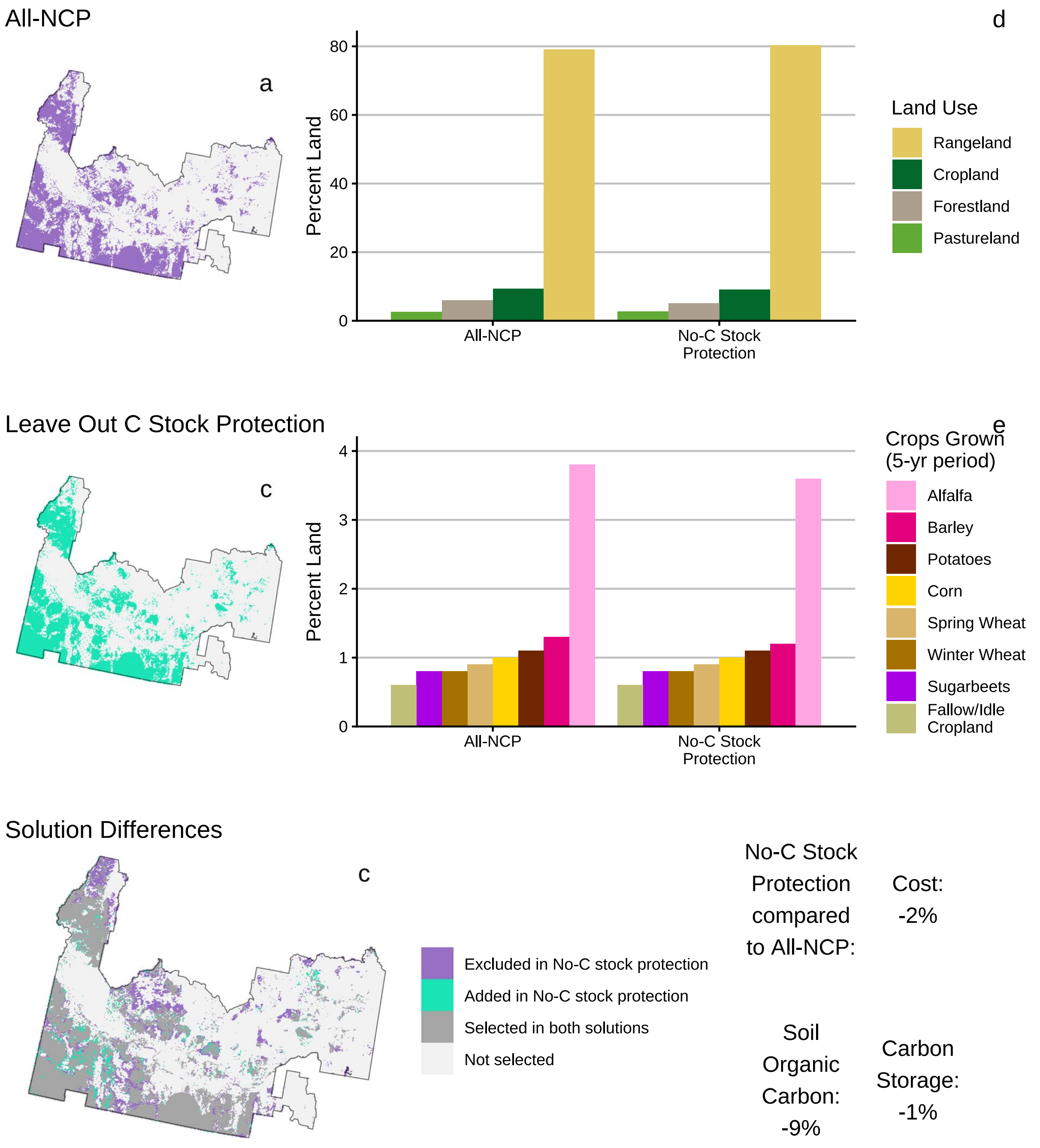

Fig. 6 Differences between the all-NCP solution and the Leave Out C Stock Protection (No-C Stock Protection) solution at 30% targets. **a** The All-NCP scenario includes the 14 NCP indicators selected in our sensitivity analysis. **b** The No-C Stock Protection scenario includes 12 NCP indicators, excluding the 2 selected C stock protection indicators. **c** The No-C Stock Protection solution excludes many lands included in the all-NCP solution and includes some lands that were not chosen in the all-NCP solution. Each solution has different compositions of **d** land use, **e** crops grown in a 5-yr period, cost, and NCP protected. See Online Resource D.2 for more detail.

a suite of NCP. For example, easements for ranches in the Lassen Foothills of California not only limited development and protected ranching activity, but also protected blue oak woodlands habitat that is predominantly found on private land (Morrisette 2001; Byrd et al. 2009). PALs are increasingly used in areas facing development pressure, and it will be worthwhile to consider their role in protecting a suite of NCP.

Which NCP indicators are the most important drivers of optimal land protection?

We found that food production was the most important driver of optimal land protection solutions. We expected this result because less costly federal lands tend to have many co-occurring NCP yet low agricultural quality (Halperin et al. 2023). Our SCP algorithm was driven to find the least costly lands that provide high value food and feed NCP after selecting the lowest cost lands that provided much of the other NCP. This result affirms PAL programs that prioritize protection based on land cost and food and feed NCP (Hellerstein et al. 2002; Miller 2015; Freedgood et al. 2020).

Surprisingly, we also found that second to food and feed NCP, C stock protection was the most important driver of solutions. Furthermore, excluding climate-related NCPs created solutions that didn't efficiently protect lands that provide high carbon storage and climate adaptation values. Critically, we found the additional cost to include climate NCPs is minimal. This is an important result because, unlike food and feed, climate-related NCP are rarely considered in PAL planning. Climate change will cause disruption to many NCP (Chaplin-Kramer et al. 2019; Requena-Mullor et al. 2023). Therefore, the most effective land protection will consider both current and future NCP. While there may be high-level consideration that climate change should be considered in agricultural land protection planning (Freedgood et al. 2020), in our experience, the explicit inclusion of climate change indicators in PAL planning is very limited.

Sensitivity analysis workflow

In our study, the sensitivity analysis was critical to identify both redundant and influential NCP indicators in our SCP analysis. Removing redundant inputs created a simpler all-NCP scenario so that the main drivers among and uniqueness of the NCP features could be better understood. The sensitivity analysis then revealed the most influential drivers of SCP solutions, which allowed us to quantify the impact of each influential driver on solutions.

The vast majority of SCP research does not conduct a sensitivity analysis (Neuendorf et al. 2018; Velazco et al. 2020). This is problematic because SCP results may be assumed to be fact even if their predicted protection outcomes are impossible, and implementing these uninformed decisions can lead to inefficient investments and environmental and human harm (Neuendorf et al. 2018). Sensitivity analyses overcome these problems by communicating model behavior and increasing transparency in conservation planning (Neuendorf et al. 2018). SCP assumes the input layers (here, the NCP data) are accurate; however, input layers have different levels of uncertainty. Our sensitivity analysis can be used as a first assessment of solution uncertainty. If the most influential layers are highly uncertain, the solution will also have high uncertainty. In these cases, additional methods that deal with uncertainty in SCP, such as Monte Carlo analysis, are necessary (Neuendorf et al. 2018).

Limitations and future directions

Spatial analyses of this scale require various assumptions. For example, we assume that land in a given land use category (e.g. all croplands) are managed the same, and thus provide the same level of NCP. While conventional land use practices dominate in our study area, there are small pockets of non-conventional land uses, such as regenerative agriculture and sustainable landscaping. It was beyond the scope of this study to systematically map alternative land management strategies. We suggest future research explore systematic approaches to incorporating the effects of different management strategies on NCP and determining their effect on SCP solutions. Relatedly, our SCP solutions can point practitioners to general priority areas for protection, but land trusts and other land protection agencies should still use local knowledge and additional criteria in combination with landowner willingness to create PALs that provide high and/or diverse NCP.

The NCP framework has been criticized for inappropriate valuation measures, inadequate consideration for demand and access, and issues of justice and equity (Chan and Satterfield 2020). We used this framework because we contend that a greater understanding of NCP trade-offs associated with land use change can help inform choices about land conversion or protection (Neugarten et al. 2024). However, use of the NCP framework also led us to exclude tribal lands for two reasons: (1) we were not able to integrate the context-specific NCP perspective, typical of local and indigenous knowledge systems (Díaz et al. 2018); and (2) tribal lands have a complex land tenure history that complicates land protection, especially by easements, a common form of PAL (Middeton 2011). Our study area is located within the historic lands of the Shoshone, Bannock, Newe Sogobia (Eastern Shoshone), Nimiipuu (Nez Perce), Cayuse, Umatilla, and Walla Walla peoples (Native Land Digital, n.d.). We suggest that SCP could be advanced by incorporating context-specific NCP and non-NCP frameworks, particularly from Indigenous and local perspectives, as these people play important roles in protecting land and its contributions to humans.

Conclusion

We used an NCP framework to systematically identify priority lands for protection in an area with both public and private lands. We found that private land protection is important even in a public lands-dominated landscape. In regions where food production provides economic, environmental, and cultural benefits, private land protection through PALs is vital. Agricultural land protection is growing, and systematic conservation planning for multiple NCP is an underutilized yet valuable method for PAL planning. We found that food and C stock protection were the most influential drivers of SCP results, but climate NCP are not usually included in PAL planning. Integrating climate NCP into PAL planning will result in more resilient protected area networks than may otherwise be created, especially because the additional cost to include climate NCP is minimal. This work highlights the importance of climate considerations in protected area planning at local and regional scales. The sensitivity analysis workflow that we developed for SCP analysis can be replicated in other regions to improve PAL planning by identifying underprotected NCP and targeting important NCP.

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Data Availability Original data sources are described and linked in the manuscript and Online Resource B. Datasets generated during the current study and associated R code can be accessed at: https://github.com/CarolynKoehn/Koehn_etal_2026_Key-targets-for-conservation-planning

Declarations

Competing Interests The authors declare no competing interests.

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