Biological Conservation 297 (2024) 110735

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Systematic conservation planning for private working lands: Identifying agricultural protection areas for climate solutions, biodiversity habitat, and ecosystem services

Sarah Halperin *, Carolyn R. Koehn, Kelsey K. Johnson, Jodi S. Brandt *

Human-Environment Systems, Boise State University, Boise, ID, USA

ARTICLE INFO

Keywords:
Agricultural landscapes
Ecosystem services
Optimization
Private land conservation

ABSTRACT

The escalating pace of climate change and biodiversity loss has energized endeavors to expand protected areas. Recent studies find that agricultural land may play a vital role in tackling climate change and promoting biodiversity. However, most agricultural protection areas (APAs) are implemented based solely on agricultural production characteristics, and there are limited strategies that incorporate other conservation goals. We combined Systematic Conservation Planning (SCP) principles, optimization algorithms, and the Ecosystem Service framework to identify potential APAs and explore the trade-offs in promoting the multifunctionality of agricultural land. We conducted our study in the Treasure Valley, Idaho, where we generated four optimization scenarios. 1. Agricultural Productivity 2. Climate Mitigation 3. Wildlife Habitat 4. Combined Ecosystem Services. We compared the four scenarios based on their a) ability to protect cultivated land, b) potential to contribute to climate mitigation, c) protection of important biodiversity habitat, and d) economic cost. We found that the Climate Mitigation, Wildlife Habitat, and Combined Ecosystem Services scenarios protected a more even distribution of ecosystem services without sacrificing the amount of cultivated land protected. We found that the Agricultural Productivity scenario resulted in the lowest total cost; however, the other scenarios protected a larger area at a lower cost per unit area. The inclusion of multiple objectives showed strong potential to help reach global conservation goals. Our work adds to the body of literature on the role of private land in protecting natural resources and is a starting point for future research to guide agricultural land protection.

1. Introduction

Globally, private land protection has become recognized as a key strategy for addressing climate change and biodiversity loss (Clancy et al., 2020). Recent calls such as the Half Earth Project, the Nature Conservancy's 2030 goals, and the Biden administration's commitment to protect 30 % of United States (U.S.) lands and waters by 2030 (30 × 30) have explicitly recognized the need to expand the network of protected areas (House, 2021; *The Nature Conservancy's 2022 Annual Report*, 2022; Wilson, 2016). For the U.S, the protection of 30 % of land is an ambitious goal. As of 2018, less than 15 % of current U.S. lands managed for biodiversity are permanently protected (U.S Geological Survey, 2020) and several studies suggest current protected areas have had limited success in protecting important lands for biodiversity and climate regulation (Dreiss and Malcom, 2022). To improve the overall integrity of conservation efforts in light of the ambitious 30 × 30 goals, proposed pathways emphasize the inclusion of private lands (Chapman et al., 2023).

Private lands are critical for creating connected protected networks needed to promote biodiversity (Suraci et al., 2023a; Dreiss and Malcom, 2022; Bargelt et al., 2020). For example, compared to publicly owned and managed protected lands, protected private lands are more often in areas of higher conservation priority and have higher mean species richness (Chapman et al., 2023). As agricultural lands account for almost 50 % of the land area of the United States, a large component of expanding protected areas will likely need to include legal protection for agricultural land uses and associated activities (Suraci et al., 2023b).

Agricultural protection areas (APAs), also known as agricultural preservation areas or agricultural conservation easements, are designated parcels where agricultural land is protected from conversion to non-agricultural uses. These areas are established through various mechanisms (e.g. zoning regulations, land use policies, conservation

* Corresponding author at: 1295 University Dr, Boise, ID, 83706, USA.
E-mail addresses: sarahhalperin8@gmail.com (S. Halperin), jodibrandt@boisestate.edu (J.S. Brandt).

https://doi.org/10.1016/j.biocon.2024.110735
Received 18 December 2023; Received in revised form 5 July 2024; Accepted 26 July 2024
Available online 2 August 2024

easements, or other government programs) and often involve differing levels of protection (Agricultural Protection Areas | *Utah Department of Agriculture and Food*, 2022; *Protect Farm and Ranch Land | Farmland Information Center*, n.d.). The primary goal of APAs is to protect farmland for agricultural use and to promote food production; however, there is an opportunity to manage APAs for a range of economic, social, and ecological objectives. In this paper, we explored the trade-offs across different objectives for protecting agricultural land.

The Ecosystem Service Framework is a useful tool to measure the multiple benefits of agricultural land and thereby explore the trade-offs across different objectives (Millennium Ecosystem Assessment (MEA), 2005). Previous studies have shown that agricultural land can provide many ecosystem services (ES) including food production, combating climate change through carbon storage, contributions to wildlife habitat, soil and water quality regulation, and cultural, scenic, and recreational value (e.g. Power, 2010). Focusing on the ES that are key priorities for 30 × 30, recent studies such as Suraci et al. (2023b) and Grass et al. (2019) find that agricultural land and its proper management are necessary to preserve high-quality habitat. Additionally, agricultural lands can meaningfully contribute to carbon storage through a portfolio of land stewardship options (i.e. no-till, grazing land management, etc.) (Fargione et al., 2018). Estimates indicate that optimizing the soil's capacity to retain carbon accounts for 12 % of possible climate change mitigation achieved through improved management of grassland and agricultural areas (Bossio et al., 2020). Despite evidence of agriculture to provide benefits beyond food production, most decisions regarding the protection of agricultural land do not consider multiple objectives.

Prioritizing agricultural land protection in the face of multiple objectives remains a challenge because its various benefits seldom overlap spatially (Halperin et al., 2023). One solution to this challenge is systematic conservation planning (SCP) - a framework that incorporates multiple goals for efficient and effective protection at landscape scales (Margules and Pressey, 2000). SCP has been primarily applied in the context of biodiversity conservation, but has additionally been used for invasive species control, fire management, and the conservation of various other ES (Villarreal-Rosas et al., 2020; McIntosh et al., 2017). However, despite its vast application, to our knowledge there is limited application of SCP to agricultural protection.

This analysis developed a framework for prioritizing agricultural land protection based on multiple objectives. We applied this framework to the Treasure Valley region in Idaho as a case study to represent the potential benefits of APAs in regions with a strong agricultural economy. We used SCP- based spatial optimization analyses to generate four objective-based scenarios. Each scenario assumed the ecosystem service of food production potential will remain a priority for agricultural protection but explored trade-offs in including additional ES. We then examined how priority APAs from these alternative scenarios differed in the following outcomes:

i) spatial pattern, their effectiveness in protecting cultivated land, and agricultural land (i.e. cultivated land and rangeland) of varied quality.
ii) effectiveness in protecting a chosen set of ES (food production potential, carbon storage, habitat quality, recreation, nitrogen retention) provided by agricultural land.
iii) effectiveness in achieving national 30 × 30 conservation targets for climate change and biodiversity loss.
iv) economic cost.

2. Methods

2.1. Study area

We used the Treasure Valley, ID (Ada and Canyon County, 4301 km^2) to explore the application of SCP to protect agricultural lands as it embodies common threats and characteristics of regions that could benefit from APA programs (Fig. 1). The Treasure Valley stands out for its semi-arid climate, intricate topography, as well as irrigated agricultural land. It features distinct hot-spots of population growth that have resulted in notable agricultural land loss (Narducci et al., 2019). There are a total of 389,944 acres of farmland in the Treasure Valley (USDA National Agricultural Statistics Service, 2022). Idaho is the 5th largest state agriculture economy, with food processing equating to 17 % of the state's total economic output in sales, and over $2.6 billion of agricultural products sold worldwide (*Idaho Agriculture Facts and Statistics – Idaho State Department of Agriculture*, n.d.).

2.2. Optimization analysis

We generated a series of four SCP-based spatial optimizations (scenarios) to identify priority APAs given differing objectives. We used multiple ES as metrics to identify APAs, as traditional conservation metrics (e.g. biodiversity) do not encompass the many benefits of agricultural lands. The four optimization scenarios differed by the number of ES included; however, each analysis had the goal to preferentially select areas with a high supply of ES at the least cost. We used this technique to identify areas that are more likely to be implemented because they balance conservation benefit and cost (Margules and Pressey, 2000).

To conduct the spatial optimizations, we used an integer linear programming approach using the prioritizr package in R with Gurobi solver (Gurobi Optimization LLC, 2023; Hanson et al., 2022). Prioritizr is designed to help build and solve conservation planning problems by generating a mathematical optimization problem and solving it to generate a solution. We created an optimization problem using a minimum set objective that seeks to select areas that minimizes cost, while meeting targets for conservation features. The package requires two spatial data inputs, conservation features and a cost feature. We additionally chose to include a locked-out feature. In the optimization problem, all features are restricted to a study area and are divided into discrete areas termed planning units. Targets are specified to determine how much of a feature should ideally be represented by solutions (Beyer et al., 2016; *Package Overview*, n.d.). For additional details, please see Appendix B.

In this analysis, we used ES as conservation features and an estimate of land value as a measure of relative cost. Following the Millennium Ecosystem Assessment (MEA) (2005) classification system, we included one provisioning ES (i.e. food production potential), two regulating ES (i.e. carbon storage and nitrogen retention), one cultural ES (i.e. recreation), and one supporting ES (i.e. habitat quality). These chosen ES provide various benefits to the people in the Treasure Valley. For example, food production potential contributes to food supply and security, economic stability, and preserves the cultural heritage of the region. Carbon storage, nitrogen retention, and habitat quality support the functioning of the region's ecosystems, aiding in, for example, climate regulation, protection from extreme weather events, and enhancing water, soil, and air quality. Lastly, recreation contributes to nature-based experiences such as fishing, hiking, or swimming (Narducci et al., 2019; Díaz et al., 2018; MEA, 2005). We chose our suite of ES based on previous survey-based research that identified them as highly important to people in the study area (Narducci et al., 2019). Food production potential was represented by the Productivity, Versatility, and Resiliency (PVR) dataset, which integrates factors of soil suitability, crop type and growing season length, and land cover use (Conservation Science Partners and American Farmland Trust, 2020; Appendix A.1). Please see Appendix A.2 and Halperin et al. (2023) for detailed methods of the spatial representation of carbon storage, habitat quality, recreation, and nitrogen retention. It is important to note that in this analysis we only calculated the potential benefit provided by nature (i.e. the biophysical aspect). We estimated conservation costs for each scenario using a spatial dataset of estimated private land values (USD/Ha) calculated across the contiguous United States, which represents the cost of purchasing lands outright (Nolte, 2020). We converted the cost to

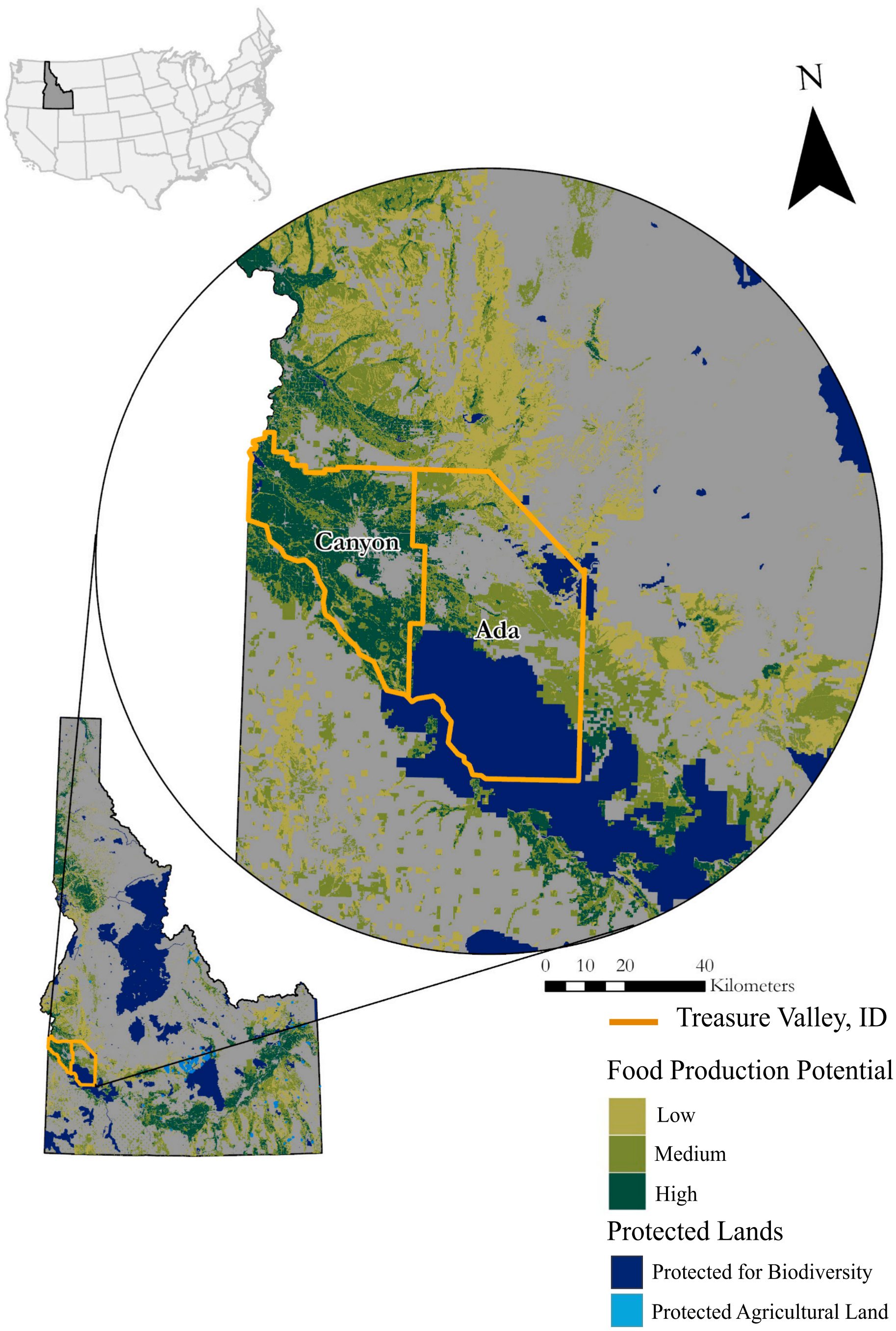

Fig. 1. Map of Treasure Valley, ID; food production potential across Idaho (Appendix A.1; Conservation Science Partners and American Farmland Trust, 2020) and protected lands for biodiversity according to USGS-GAP 2.0 database (GAP status 1 or 2) (Appendix A.4; U.S. Geological Survey, 2020) and protected agricultural lands (Protected Agricultural Lands Database, American Farmland Trust, 2023). Food production potential values were not available for federal land. There is no federal land in the Treasure Valley, so areas without food production potential in our study area are non-agricultural.

an average cost per km^2 (million USD/km^2; Appendix A.3).

The analysis was restricted to agricultural land by masking all ES to areas that have a food production potential value (Appendix A.1). This represents land that is currently or could potentially be used for agricultural purposes including both cultivated land and rangelands. We included rangelands because rangelands, while typically on marginal land in terms of soil quality, topography, or limited water, they are still considered agricultural land (Conservation Science Partners, 2020). We used the US Geological Survey GAP (USGS-GAP 2.0) Protected Areas Database of the US to exclude currently protected areas (GAP Status Codes 1 or 2) (Appendix A.4; U.S. Geological Survey, 2020). Therefore, pixels eligible for selection in each solution (2215 km^2) were lands not currently protected and with potential to be used for agricultural purposes.

Targets were based on the percentage of each ES included in the optimization analysis. For example, a 30 % target required 30 % or more of the total amount of each included ES to be within the identified APA, with total defined as the sum of ES value in all eligible pixels. We ran optimization models for targets that increased from 0 % to 40 % in increments of 5 % to visualize the growth of APAs. For this analysis, we focused on the solutions for 30 % targets, which we will refer to as solution-30, to match 30 % area-based conservation targets (30 × 30).

We ran four optimization scenarios: 1. Agricultural Productivity 2. Climate Mitigation 3. Wildlife Habitat 4. Combined Ecosystem Services. The Agricultural Productivity scenario identified APAs solely based on food production potential. The Climate Mitigation scenario identified APAs based on food production potential and carbon storage. The Wildlife Habitat scenario identified APAs based on food production potential and habitat quality. The Combined Ecosystem Services scenario identified APAs based on food production potential, carbon storage, habitat quality, recreation, and nitrogen retention (Appendices A.1, A.2). We designed the Agricultural Productivity scenario to reflect the current primary goal of APAs to promote food production, while the other three scenarios reflect alternate strategies to protect the multifunctionality of agricultural land. We included food production potential in each scenario because we assumed that it would remain a priority for APAs. Please see Appendix B for a visualization of the workflow and description of inputs for each scenario.

To align all spatial layers for input into the prioritizr package, we resampled from 30 km^2 to 1 km^2 using bilinear interpolation and projected to EPSG:5070 NAD83 Albers Equal Area. We resampled to 1 km^2 to represent roughly the average size of an APA protected under Purchase of Agricultural Conservation Easement programs (Sallet, 2022). All data was input into prioritizr in raster form so planning units were defined as a 1 km^2 cell.

The final output is a single optimal solution map of priority areas for set targets for each scenario. The four scenarios were then used to address our research questions presented in the following subsections (2.2.1–2.2.4). We used R v4.1.2 for presentation, data manipulation, and analysis (RStudio Team, 2022).

2.2.1. APA spatial pattern and effectiveness in protecting cultivated land and agricultural land of varied quality

We compared APA selection based on a) percent of total cultivated land protected, and b) the amount of low, medium, and high-quality agricultural land. We defined cultivated land as the combination of cropland and pasture classes of the National Land Cover Database (NLCD) for 2016 (Dewitz, 2019; Appendix A.5; Appendix Fig. B.2). While agricultural land includes both cultivated land and rangelands, we assessed only cultivated land because in the Intermountain West cultivated lands are typically more productive than rangelands in terms of food and economic potential (*Idaho Agriculture Facts and Statistics – Idaho State Department of Agriculture*, n.d.). Percent cultivated land protected represents the amount of cultivated land in the APA divided by the total amount of cultivated land in the Treasure Valley.

We created a categorial land quality variable with three classes -high, medium, and low quality – using the PVR dataset following Halperin et al. (2023). The PVR metric ranges from 0 to 1 with higher values representing agricultural land that is the most suitable for long-term cultivation. To explore across agricultural land quality classes, $^1/_3$ quantiles were assigned to divide the 0–1 values into three classes (high, medium, and low quality) (Appendix A.1). We report the amount of low, medium, and high-quality agricultural land, totaling to 100 % of each solution-30 priority area to describe its agricultural quality composition.

2.2.2. APA effectiveness in protecting the chosen ES

We compared the percent of ES protected within each APA for each scenario (Appendix Fig. B.3). The optimization model only seeks to reach targets for conservation features included in the optimization problem, therefore, we wanted to compare how well each of the four scenarios protected ES even if they weren't included in the optimization analysis. For example, the solution-30 of the Agricultural Productivity scenario included only a target to protect 30 % of food production potential, but it was not required to protect any of the other ecosystems services. Therefore, to understand how well the APA would perform in terms of the other four ES we calculated the percent of total ES in each APA (the amount of ES supply within a solution-30 divided by the total amount of ES supply that could be selected).

2.2.3. APA contribution to 30 × 30 conservation goals

We explored the potential conservation value of each identified APA (Appendix Fig. B.4). We used three conservation value indices (Climate, Biodiversity, Combined) produced by Suraci et al. (2023a) (Appendix A.6). The Climate index incorporated information on current carbon storage and the expected change in local and regional climate conditions. The biodiversity index incorporated species richness and threat status, an estimate of ecological integrity of the landscape, and the ability of the landscape to support connectivity. The combined index identified high-value landscapes that account for the trade-offs between climate and biodiversity objectives. We included these conservation indices to provide a general understanding of how well the four scenarios can contribute to biodiversity and climate goals. We determined the percent of the APA that is of higher conservation value (i.e. top $^1/_3$ quantile of each index) and total area of higher conservation value in km^2. Both the percent of higher conservation value and total area were included to provide information on the composition of the APAs and total area identified as a high priority for meeting conservation targets for climate change and biodiversity loss. These calculations were included in addition to the five ES as an independent, post-hoc analysis to measure the efficacy of the optimization solutions.

2.2.4. APA cost

We compared the total cost (reported as billion USD) and the average cost (reported as million USD/km^2) of each identified APA. We reported the total cost in billion USD and average cost in million USD/km^2 for each scenario for targets between 0 and 40 %.

3. Results

3.1. APA spatial pattern and effectiveness in protecting cultivated land and agricultural land of varied quality

We found that the selection of protected areas varied across the landscape for the four scenarios, with the Agricultural Productivity scenario protecting areas primarily in the northwest region of the Treasure Valley and the Climate Mitigation, Wildlife Habitat, and the Combined Ecosystem Services, scenarios protecting additional land in the northeastern and southeastern regions of the Treasure Valley. Overall, we observed a high level of overlap between solutions, yet many areas only appeared in one scenario (Fig. 2).

We found that the amount of high, medium, and low-quality agricultural land protected varied under each optimization scenario (Fig. 3; Appendix C.1). Solution-30 for the Agricultural Productivity scenario comprised of 96 % high-quality, 4 % medium quality, and 0 % low quality agricultural land. The Climate Mitigation, Wildlife Habitat, and Combined Ecosystem Services scenarios selected more evenly across agricultural land quality classes, while still selecting a higher proportion of highest quality lands (Fig. 3B; Appendix C.1). Additionally, solution-30 for the Agricultural Productivity scenario protected the most cultivated land (30 % of cultivated land in the Treasure Valley); whereas the other scenarios protected at most 25 % (Fig. 3A; Appendix C.1).

3.2. APA effectiveness in protecting the chosen ES

We found that the supply of ES protected varied across the four scenarios, with the greatest difference between the Agricultural Productivity scenario and the other three scenarios (Fig. 4). For solution-30, the Agricultural Productivity scenario, as expected, protected the most food production potential (30 % of total), but the least of the other ES (i.e. 17 % of total carbon storage, 9 % of total habitat quality, 20 % of total nitrogen retention, and 6 % of total recreation). The Climate Mitigation scenario protected at least 30 % of all ES except nitrogen retention (29 %). The Wildlife Habitat scenario protected 30 % of habitat quality and crop production, but carbon storage (27 %), nitrogen retention (27 %) and recreation (24 %) were below 30 %. Lastly, the Combined

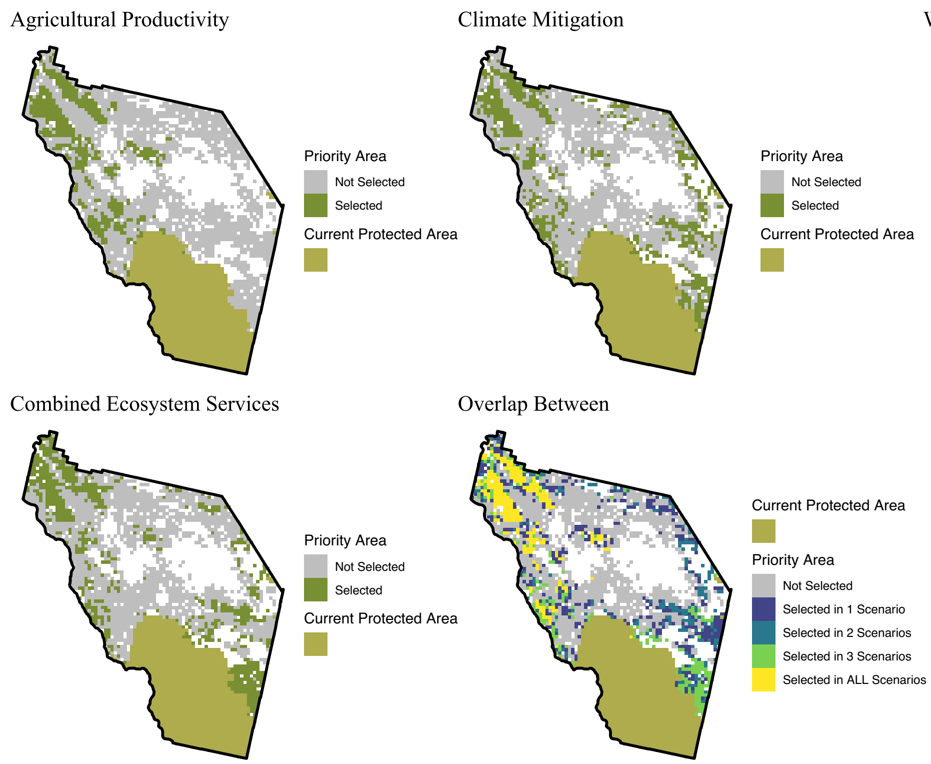

Fig. 2. Map of Solution-30 for each scenario. Solution-30 represents APAs that achieve 30 % of the target(s) at the least cost.

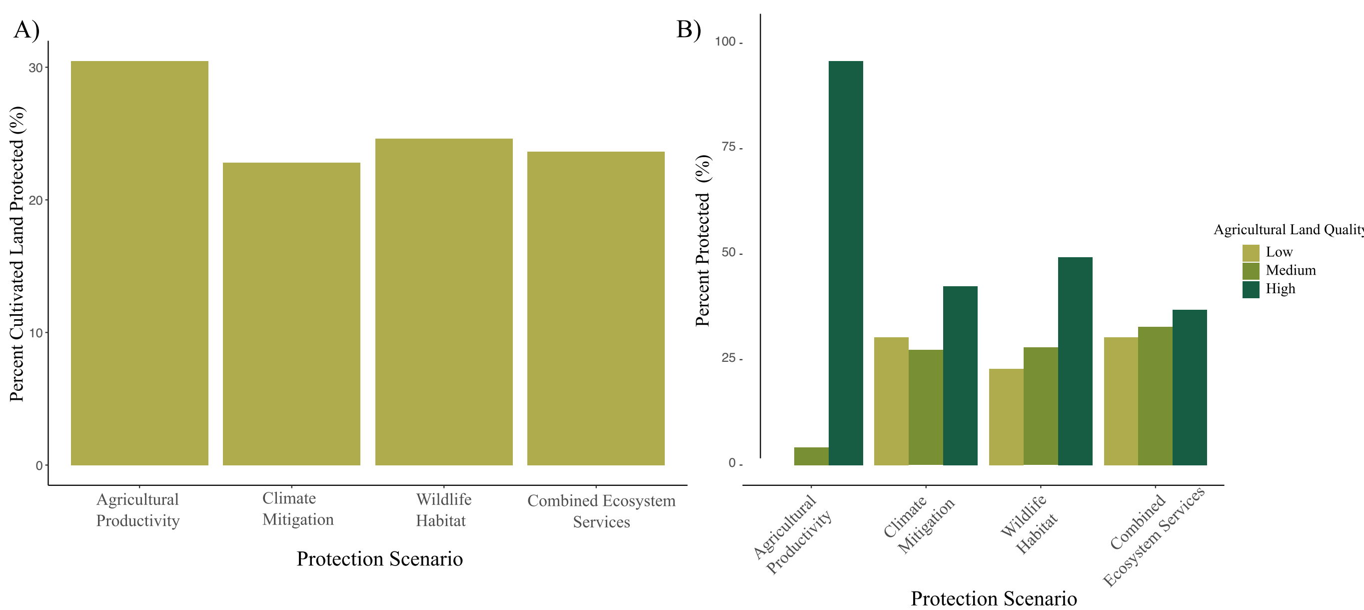

Fig. 3. A) Percent of total cultivated land in the Treasure Valley protected by solution-30 Agricultural Protection Areas for each of the four scenarios. B) The compositional percent of solution-30 Agricultural Protection Areas that is low, medium, and high-quality agricultural land for each of the four scenarios.

Ecosystem Services scenario protected the highest percentage of ES with all ES meeting the 30 % target and habitat quality and recreation exceeding the target at 35 % and 33 %, respectively (Fig. 4; Appendix C.2).

3.3. APA contribution to 30 × 30 conservation goals

We found that the potential contributions of APAs in reaching 30 × 30 conservation targets varied depending on the scenario. The Agricultural Productivity scenario contributed least; with solution-30 containing 0 %, 13 %, and 0 % higher conservation value pixels based on the Combined, Climate, Biodiversity indexes, respectively (Fig. 5A). This translates to, on average across the three conservation value indexes, 20 km^2 of higher conservation value protected under the Agricultural Productivity scenario (Fig. 5B). Solution-30 for the Climate Mitigation scenario contained 10 %, 25 %, and 16 %, solution-30 of the Wildlife Habitat scenario contained 15 %, 22 %, 22 %, and solution-30 of the Combined Ecosystem Services scenario contained 10 %, 19 %, and 17 % of higher conservation value for the Combined, Climate, and Biodiversity indexes, respectively (Fig. 5A). This translates to on average across

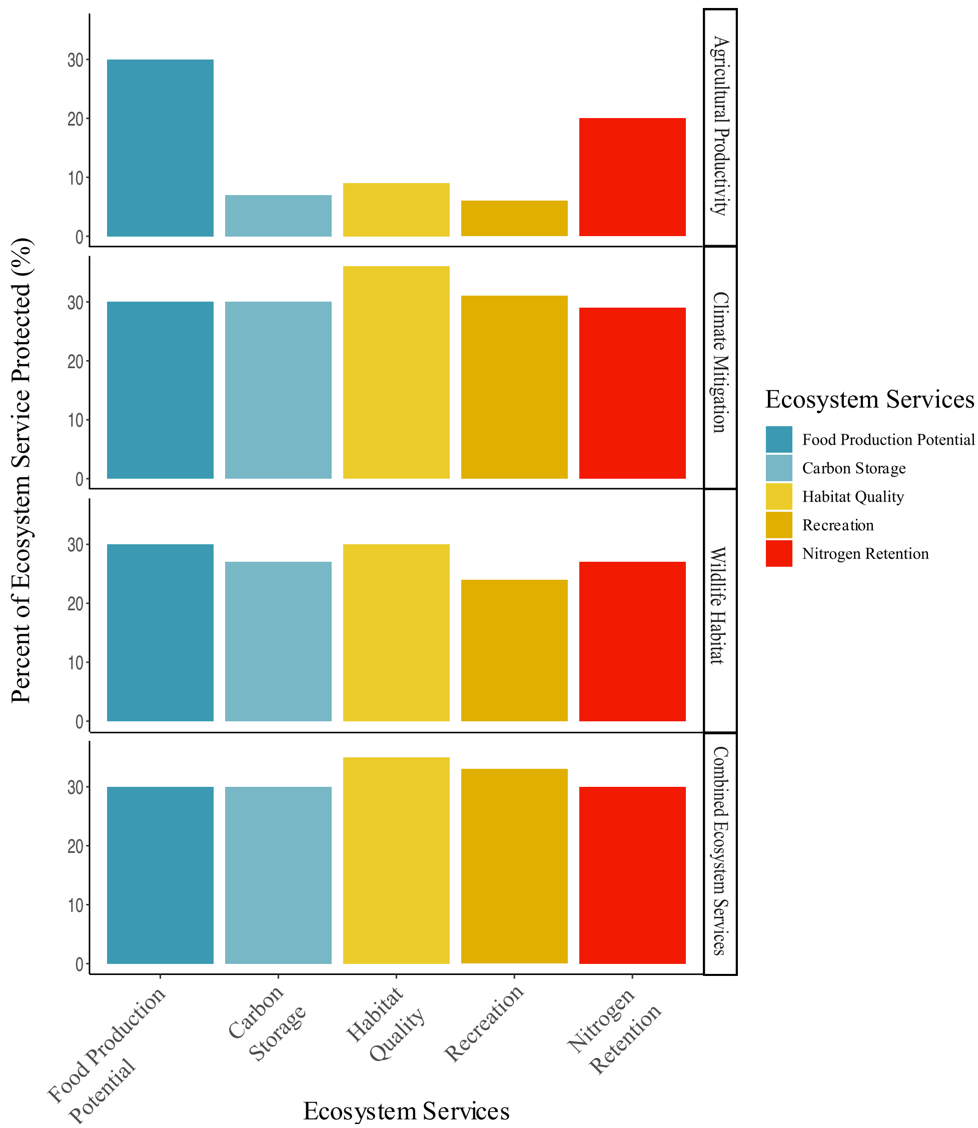

Fig. 4. The percent of total supply of the four ecosystem services and food production potential protected by solution-30 for each scenario. Total supply is the sum of ES for all eligible pixels.

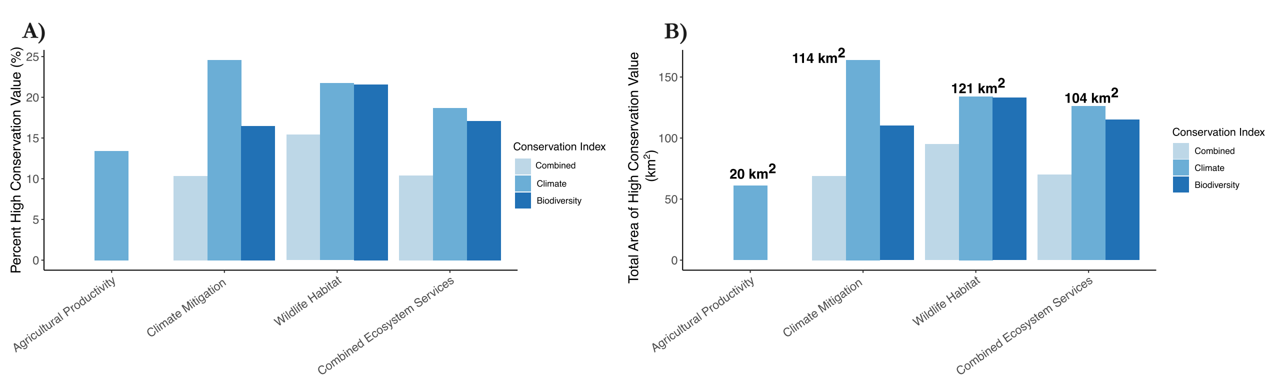

Fig. 5. A). The percent of the APA that is higher conservation value pixels (i.e. in top $^{1}/_{3}$ quantile) for solution-30 for each scenario. B) The total area of higher conservation value (km^2) (i.e. in top $^{1}/_{3}$ quantile) for solution-30 for each scenario. In bold above each protection scenario is the average area (km^2) protected of high conservation value across the three conservation indices for each scenario.

the three conservation value indexes 114 km^2, 121 km^2, and 104 km^2 of higher conservation value protected under the Climate Mitigation, Wildlife Habitat, the Combined Ecosystem Services scenarios, respectively (Fig. 5B; Appendix C.3).

3.4. APA cost

Based on the fair market value of private land (USD/km^2), we found that the Climate Mitigation and the Combined Ecosystem Services scenarios had the highest cost. For solution-30, the Agricultural Productivity scenario had an estimated cost of $1.96 billion, the Combined Ecosystem Services scenario had an estimated cost of $2.78 billion, the Climate Mitigation scenario had an estimated cost of $2.75 billion, and the Wildlife Habitat scenario had an estimated cost of $2.55 billion (Table 1). The total cost increased when additional conservation objectives were included because a higher number of pixels were selected. For example, the solution-30 for the Agricultural Productivity scenario selected 455 pixels whereas the Climate Mitigation scenario selected 667 pixels (Table 1). When comparing the cost/km^2 however, we found that the Agricultural Productivity scenario was the most expensive at $4.3 million/km^2; whereas all other scenarios were $4.1 million/km^2 (Table 1). So, while the Agricultural Productivity scenario was the cheapest in terms of total cost, it on average protects higher cost pixels, whereas the other three scenarios protect more, but on average cheaper land. Generally, we found that the total cost increased, but the cost/km^2 decreased when we included alternative objectives beyond agricultural-specific goals.

4. Discussion

4.1. Priority area selection for agricultural land protection shifts when alternative conservation objectives are considered

A key motivation for our study was to examine whether multiple objectives should be considered in the designation of APAs. To explore this concept, we examined four distinct optimization scenarios to select APAs. We found that each of the four scenarios yielded different land protection outcomes and, therefore, our results suggest that integrating multiple objectives will likely impact the contribution of APAs to conservation efforts. Our findings showed that selection of APAs varied spatially and across agricultural land quality. In particular, we found that under the Agricultural Productivity scenario, agricultural land of higher quality was almost exclusively selected for protection; whereas when APAs were expanded to include other benefits associated with agriculture land, areas selected for protection were more evenly distributed across agricultural land quality (Fig. 3B). This is expected as previous research found that there are trade-offs in ES across agricultural land quality and that the ES from agricultural land often do not overlap (Halperin et al., 2023). The inclusion of multiple objectives had a limited impact on the amount of cultivated land protected and may provide a more diverse range of benefits such as future food security, recreation, and water quality (Halperin et al., 2023). Previous studies have shown that both high-yield, intensive agriculture and less extractive agricultural practices are needed to meet increasing food demands (Grau et al., 2013). Therefore, our findings suggest that current mechanisms to protect agricultural land that focus solely on agricultural-specific objectives may have limited success in supporting long-term viability of agriculture.

4.2. Priority area selection impacts the potential amount of ES under protection

Alternative conservation objectives altered the supply of ES protected. We found that for the Agricultural Productivity scenario, there was limited protection of any of the ES beyond food production potential. Alternatively, we found that when additional objectives were included, the APAs protected ES without sacrificing agricultural-specific goals. As such, this analysis suggests that it is possible to systematically identify APAs that protect agricultural productivity, while simultaneously protecting the many other benefits agricultural land provides.

Building off the existing body of literature on multi-objective conservation planning (e.g. Quintas-Soriano et al., 2021), we show how to apply a multi-objective prioritization framework to agricultural land protection that balances multiple ES. Previous work has suggested that including multiple ES in understanding agricultural lands could help achieve conservation, sustainability, and food security goals (Halperin et al., 2023). Our work builds on those findings and suggests a landscape-level systematic approach to identifying APAs that considers the trade-offs between ES and agricultural productivity. This analysis also provides further evidence that holistic conservation efforts lead to an increase in overall conservation impact. For example, previous research has shown that to optimize effectiveness, networks of protected areas must be representative of ecosystem processes (Ivanova and Cook, 2023). By integrating ES into the designation of APAs, we show how targeted conservation efforts can increase the integrity and impact of agricultural land protection.

4.3. Agricultural land protection can add to protected area networks and aid in reaching global conservation targets

A driving motivation for our study was to specifically understand the benefits of integrating a systematic landscape-level approach to agricultural land protection as a way to address important conservation challenges. While this analysis highlights the role that agricultural lands can play in meeting 30 × 30 conservation goals, it also illustrates how objectives can influence the degree to which agricultural lands contribute to these goals. Based on the conservation indices generated by Suraci et al. (2023a), we found that the four scenarios protected different levels of higher conservation value land. Notably, the Agricultural Productivity scenario emerged as the least effective at

Table 1
Average cost (million USD/km^2), total cost (billion USD), and total area (km^2) protected for each optimization scenario for targets between 0 % and 40 %. Solution-30 is bolded.

Target	Agricultural productivity			Climate mitigation			Wildlife habitat			Combined ecosystem services		
	Million USD/km^2	Total cost billion USD	Total pixels	million USD/km^2	Total cost billion USD	Total pixels	Million USD/km^2	Total cost billion USD	Total pixels	Million USD/km^2	Total cost billion USD	Total pixels
0	0.0	0.00	0	0.0	0.00	0	0.0	0.00	0	0.0	0.00	0
5	4.2	0.29	70	4.0	0.45	113	4.1	0.38	93	4.0	0.45	113
10	4.2	0.61	143	4.0	0.90	224	4.0	0.86	214	4.0	0.91	225
15	4.3	0.93	218	4.1	1.35	332	4.1	1.28	313	4.1	1.36	334
20	4.3	1.27	296	4.1	1.81	443	4.1	1.69	413	4.1	1.82	446
25	4.3	1.61	374	4.1	2.28	555	4.1	2.13	516	4.1	2.29	558
30	**4.3**	**1.96**	**455**	**4.1**	**2.75**	**667**	**4.1**	**2.55**	**617**	**4.1**	**2.78**	**673**
35	4.3	2.33	538	4.1	3.22	780	4.1	3.00	723	4.1	3.26	789
40	4.3	2.70	623	4.1	3.70	893	4.2	3.45	831	4.1	3.75	903

protecting higher conservation value pixels, as it protected no higher conservation value pixels for both the Combined and Biodiversity indices and a limited amount of higher conservation value pixels for the Climate index (13 %) (Fig. 4; Appendix C.3).

Our work aligns with previous research that supports both private and working lands potential to improve conservation outcomes (e.g. Chapman et al., 2023; Bargelt et al., 2020) and provides further justification for including ES in conservation decision (e.g. Villarreal-Rosas et al., 2020). However, our work shows that caution should be taken to maximize the benefits of agricultural land. Our results suggest that the current methods of protection which solely prioritize agricultural productivity will likely not contribute significantly to other conservations goals. In order to improve the integrity of future conservation efforts and expand private protected networks, there will need to be improved strategies that consider factors other than agricultural productivity.

4.4. Priority area selection should consider cost-effectiveness

When conservation budgets are limited, cost is a key factor in conservation decisions. In this analysis, we found that the Agricultural Productivity scenario required the least amount of land to reach the solution-30 target, and therefore had the lowest total cost of the four scenarios. However, the Agricultural Productivity scenario on average protected higher cost land than the other three scenarios (Table 1). The other scenarios identified APAs that reach agricultural productivity targets while simultaneously protecting other crucial benefits, at a lower cost/km^2. Our results suggest that integrating alternative objectives may prioritize cheaper land on average but require more land to reach set objectives and therefore, come at a higher total cost. Therefore, it is expected that including additional objectives into conservation strategies will likely come at a higher total cost, but will protect a larger area of land, will protect additional benefits, and will likely have a lower cost/km^2. While the concept of nature as capital and accounting for the economic values of nature is controversial (Duke et al., 2013), by integrating cost into the designation of APAs we provide additional information that shows that targeted conservation efforts can increase the integrity, impact, and cost-effectiveness of agricultural land protection.

4.5. Limitations and next steps

Our analysis included ES, which were chosen and developed based on their importance to the region, relevance to agriculture, and current and available data and methodologies. However, we only included the biophysical aspect of the ES. We suggest future research include a more nuanced relationship between people and nature such as the direct benefit people obtain, demand for ES, or vulnerable human populations (Villarreal-Rosas et al., 2020; Chaplin-Kramer et al., 2019). Additionally, we suggest future research continue to explore systematic approaches for APA selection including additional relevant objectives to promote the viability of agricultural regions. We strongly urge researchers and managers to match conservation objectives to regional priorities. For example, if land managers were primarily concerned with protection of cultivated lands and potential to mitigate climate through carbon storage, it would be important to restrict the analysis to cultivated land and include carbon storage as the primary objective.

We focused this study on understanding the trade-offs in promoting the multifunctionality of agricultural land in APA designation. We tested the sensitivity of the solutions to varying targets and objectives and primarily focused on solutions that met 30 % targets; however, quantifying the sensitivity of the model to target variation and individual inputs was outside the scope of our work. Overall, the incorporation of sensitivity analysis in optimization analyses is under-developed (but see Roura-Pascual et al., 2010), and we suggest future research focus on exploring methodologies to understand the sensitivity of priority area designation to all aspects of model generation.

In this study, we used the estimated fair market value of private lands as a comparable one-time cost for acquiring a parcel (Nolte, 2020). We believe that this a good first-order approximation; however, we acknowledge that Idaho's status as a non-disclosure state may limit how well these data reflect land prices in the state. Furthermore, while these data represent the cost of acquiring land, it does not reflect the non-market values of the numerous ES provided by agricultural land – a key piece of information for cost-effective conservation decisions that balance the cost of conservation and the *total* benefits of the protect land (Duke et al., 2013). The collaboration of planning specialists with social and economic scientist will enhance the likelihood of successful APA implementation, advance our understanding of the economic and social consequences associated with APAs, and provide more precise assessments of the monetary value of ES.

Our study was conducted at the regional scale, for a single case study, and we acknowledge that the results may be different for other study areas, or if conducted at a national or global scale. The potential for agriculture to provide benefits at a global scale has been widely recognized (e.g. Bossio et al., 2020) and thus our regional study can serve as a model for future studies that explore the potential of agricultural land protection at larger scales. We suggest future research reproduce and validate our work across regions and scales to explore the heterogeneity in benefits that agricultural land may provide and the total capacity of agricultural land to contribute to global conservation goals. Lastly, we acknowledge that our results may differ depending on local land use planning restrictions, social-ecological context, as well as national or global context (Williamson et al., 2018; Margules and Pressey, 2000). We urge strong consideration in the objectives that are prioritized to reduce the risk of social inequity and in order to match community concerns.

5. Conclusion

We used a common methodology in biodiversity conservation and applied it to the protection of agricultural land to protect multiple ES. We improved our understanding and provided further justification for the need for increased land conservation and highlighted the importance of private land protection efforts to achieve conservation targets. We find that a focus solely on protecting private agricultural lands opportunistically, without a landscape level and multi-objective approach may limit private lands potential to maximize ES and contribute to global conservation targets.

We recommend management solutions that support balancing trade-offs between agricultural viability and conservation efforts. Such efforts will likely take coordinated efforts across state, local, and federal agencies to scale-up actions, maximize benefits, and find solutions that can combat the challenge of managing multiple objectives. We anticipate that our findings will be a starting point for future research and discussion on ways to increase investment in private land conservation.

Funding

This work was supported by USDA AFRI NIFA [67019-29458, 2019]; USDA AFRI NIFA [09786, 2021].

CRediT authorship contribution statement

Sarah Halperin: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Carolyn R. Koehn:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Kelsey K. Johnson:** Writing – review & editing, Conceptualization. **Jodi S. Brandt:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110735.

References

American Farmland Trust, 2023. Farmland Information Center. American Farmland Trust, Northampton, MA. URL. https://farmlandinfo.org/statistics/pald/. (Accessed 12 September 2023).

Bargelt, L., Fortin, M.-J., Murray, D.L., 2020. Assessing connectivity and the contribution of private lands to protected area networks in the United States. PLoS One 15, e0228946. https://doi.org/10.1371/journal.pone.0228946.

Beyer, H.L., Dujardin, Y., Watts, M.E., Possingham, H.P., 2016. Solving conservation planning problems with integer linear programming. Ecol. Model. 328, 14–22. https://doi.org/10.1016/j.ecolmodel.2016.02.005.

Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R.J., Von Unger, M., Emmer, I.M., Griscom, B.W., 2020. The role of soil carbon in natural climate solutions. Nat Sustain 3, 391–398. https://doi.org/10.1038/s41893-020-0491-z.

Chaplin-Kramer, Rebecca, Richard P. Sharp, Charlotte Weil, Elena M. Bennett, Unai Pascual, Katie K. Arkema, Kate A. Brauman, et al. "Global Modeling of Nature's Contributions to People." *Science* 366, no. 6462 (2019): 255–58. https://doi.org/10.1126/science.aaw3372.

Chapman, M., Boettiger, C., Brashares, J.S., 2023. Leveraging private lands to meet 2030 biodiversity targets in the United States. Conservation Science and Practice 5, e12897. https://doi.org/10.1111/csp2.12897.

Clancy, N.G., Draper, J.P., Wolf, J.M., Abdulwahab, U.A., Pendleton, M.C., Brothers, S., Brahney, J., Weathered, J., Hammill, E., Atwood, T.B., 2020. Protecting endangered species in the USA requires both public and private land conservation. Sci. Rep. 10, 11925 https://doi.org/10.1038/s41598-020-68780-y.

Conservation Science Partners, 2020. Description of the Approach, Data, and Analytical Methods Used for the Farms Under Threat: State of the States Project. Version 2.0. Final Technical Report (Truckee, CA).

Conservation Science Partners and American Farmland Trust, 2020. Productivity, versatility, and resiliency in 2016. https://survey123.arcgis.com/share/3f8d2e46cec64288b53d235fa7cf7d40.

Dewitz, J., 2019. National Land Cover Database (NLCD) 2016 Products: U.S. Geological Survey Data Release. https://doi.org/10.5066/P96HHBIE.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., Hill, R., Chan, K.M.A., Baste, I.A., Brauman, K.A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P.W., van Oudenhoven, A.P.E., van der Plaat, F., Schröter, M., Lavorel, S., Aumeeruddy-Thomas, Y., Bukvareva, E., Davies, K., Demissew, S., Erpul, G., Failler, P., Guerra, C.A., Hewitt, C.L., Keune, H., Lindley, S., Shirayama, Y., 2018. Assessing nature's contributions to people. Science 359, 270–272. https://doi.org/10.1126/science.aap8826.

Dreiss, L.M., Malcom, J.W., 2022. Identifying key federal, state, and private lands strategies for achieving 30 × 30 in the United States. Conserv. Lett. 15, e12849 https://doi.org/10.1111/conl.12849.

Duke, J.M., Dundas, S.J., Messer, K.D., 2013. Cost-effective conservation planning: lessons from economics. J. Environ. Manag. 125, 126–133. https://doi.org/10.1016/j.jenvman.2013.03.048.

Fargione, J.E., Bassett, S., Boucher, T., Bridgham, S.D., Conant, R.T., Cook-Patton, S.C., Ellis, P.W., Falcucci, A., Fourqurean, J.W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M.D., Kroeger, K.D., Kroeger, T., Lark, T.J., Leavitt, S.M., Lomax, G., McDonald, R.I., Megonigal, J.P., Miteva, D.A., Richardson, C.J., Sanderman, J., Shoch, D., Spawn, S.A., Veldman, J.W., Williams, C.A., Woodbury, P.B., Zganjar, C., Baranski, M., Elias, P., Houghton, R.A., Landis, E., McGlynn, E., Schlesinger, W.H., Siikamaki, J.V., Sutton-Grier, A.E., Griscom, B.W., 2018. Natural climate solutions for the United States. Sci. Adv. 4, eaat1869 https://doi.org/10.1126/sciadv.aat1869.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., Tiede, J., Udy, K., Westphal, C., Wurz, A., Tscharntke, T., 2019. Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. People and Nature 1, 262–272. https://doi.org/10.1002/pan3.21.

Grau, R., Kuemmerle, T., Macchi, L., 2013. Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. Current Opinion in Environmental Sustainability, Human Settlements and Industrial Systems 5, 477–483. https://doi.org/10.1016/j.cosust.2013.06.001.

Gurobi Optimization, LLC, 2023. Gurobi Optimizer reference manual. URL. https://gurobi.com. (Accessed 13 September 2023).

Halperin, S., Castro, A.J., Quintas-Soriano, C., Brandt, J.S., 2023. Assessing high quality agricultural lands through the ecosystem services lens: insights from a rapidly urbanizing agricultural region in the western United States. Agric. Ecosyst. Environ. 349, 108435 https://doi.org/10.1016/j.agee.2023.108435.

Hanson, J.O., Vincent, J., Schuster, R., Fahrig, L., Brennan, A., Martin, A.E., Hughes, J.S., Pither, R., Bennett, J.R., 2022. A comparison of approaches for including connectivity in systematic conservation planning. J. Appl. Ecol. 59, 2507–2519. https://doi.org/10.1111/1365-2664.14251.

House, T.W., 2021. Executive Order on Tackling the Climate Crisis at Home and Abroad. URL, The White House. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/. (Accessed 12 September 2023) (WWW Document).

Idaho Agriculture Facts and Statistics – Idaho State Department of Agriculture. URL. https://agri.idaho.gov/main/idaho-agriculture-facts-and-statistics/. (Accessed 8 May 2023) (n.d.).

Protect farm and ranch land | Farmland Information Center. URL. https://farmlandinfo.org/ag-toolbox/protect-farm-and-ranch-land/. (Accessed 7 May 2024) (n.d.).

Ivanova, I.M., Cook, C.N., 2023. Public and private protected areas can work together to facilitate the long-term persistence of mammals. Environ. Conserv. 50, 58–66. https://doi.org/10.1017/S0376892922000455.

Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning, 405, 11.

McIntosh, E.J., Pressey, R.L., Lloyd, S., Smith, R.J., Grenyer, R., 2017. The impact of systematic conservation planning. Annu. Rev. Environ. Resour. 42, 677–697. https://doi.org/10.1146/annurev-environ-102016-060902.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Narducci, J., Quintas-Soriano, C., Castro, A., Som-Castellano, R., Brandt, J.S., 2019. Implications of urban growth and farmland loss for ecosystem services in the western United States. Land Use Policy 86, 1–11. https://doi.org/10.1016/j.landusepol.2019.04.029.

Nolte, C., 2020. High-resolution land value maps reveal underestimation of conservation costs in the United States. Proc. Natl. Acad. Sci. 117, 29577–29583. https://doi.org/10.1073/pnas.2012865117.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. B 365 (1554), 2959–2971. https://doi.org/10.1098/rstb.2010.0143.

Package overview, Prioritizr. . URL. https://prioritizr.net/articles/package_overview.html. (Accessed 7 May 2024) (n.d.).

Quintas-Soriano, C., Gibson, D.M., Brandt, J.S., López-Rodríguez, M.D., Cabello, J., Aguilera, P.A., Castro, A.J., 2021. An interdisciplinary assessment of private conservation areas in the Western United States. Ambio. https://doi.org/10.1007/s13280-020-01323-x.

Roura-Pascual, N., Krug, R.M., Richardson, D.M., Hui, C., 2010. Spatially-explicit sensitivity analysis for conservation management: exploring the influence of decisions in invasive alien plant management. Divers. Distrib. 16, 426–438. https://doi.org/10.1111/j.1472-4642.2010.00659.x.

Rstudio Team, 2022. Rstudio: Integrated Development Environment for R (Version 1.4.2). Rstudio, PBC, Boston, MA. URL. https://www.rstudio.com. (Accessed 1 August 2023).

Sallet, 2022. State purchase of agricultural conservation easement programs permanently protect over 3.4 million acres as of January 2022. URL, American Farmland Trust. https://farmland.org/state-purchase-of-agricultural-conservation-easement-programs-permanently-protect-over-3-4-million-acres-as-of-january-2022/. (Accessed 17 August 2023).

Suraci, J.P., Farwell, L.S., Littlefield, C.E., Freeman, P.T., Zachmann, L.J., Landau, V.A., Anderson, J.J., Dickson, B.G., 2023a. Achieving conservation targets by jointly addressing climate change and biodiversity loss. Ecosphere 14, e4490. https://doi.org/10.1002/ecs2.4490.

Suraci, J.P., Littlefield, C.E., Nicholson, C.C., Hunter, M.C., Sorensen, A., Dickson, B.G., 2023b. Mapping connectivity and conservation opportunity on agricultural lands across the conterminous United States. Biol. Conserv. 278, 109896 https://doi.org/10.1016/j.biocon.2022.109896.

The Nature Conservancy's 2022 Annual Report. URL, The Nature Conservancy. https://www.nature.org/en-us/about-us/who-we-are/accountability/annual-report/2022-annual-report/–. (Accessed 17 August 2023).

U.S. Geological Survey, 2020. Protected Areas Database of the United States (PAD-US 2.1). https://doi.org/10.5066/P92QM3NT.

USDA National Agricultural Statistics Service, 2022. Census of Agriculture volume 1, chapter 2: county level data. URL. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_2_County_Level/Idaho/. (Accessed 7 May 2024).

Agricultural protection areas. URL, Utah Department of Agriculture and Food. https://ag.utah.gov/farmers/conservation-division/ag-land-preservation/–. (Accessed 21 August 2023).

Villarreal-Rosas, J., Sonter, L.J., Runting, R.K., López-Cubillos, S., Dade, M.C., Possingham, H.P., Rhodes, J.R., 2020. Advancing systematic conservation planning for ecosystem services. Trends Ecol. Evol. 35, 1129–1139. https://doi.org/10.1016/j.tree.2020.08.016.

Williamson, M.A., Schwartz, M.W., Lubell, M.N., 2018. Spatially explicit analytical models for social–ecological systems. BioScience doi:https://doi.org/10.1093/biosci/biy094.

Wilson, E.O., 2016. Half-earth: Our Planet's Fight for Life. W. W. Norton & Company.