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Linking Biodiversity and Human Wellbeing in Systematic Conservation Assessments of Working Landscapes

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Abstract: Systematic land use planning to address environmental impacts does not typically include human health and wellbeing as explicit inputs. We tested the effects of including issues related to human health, ecosystem services, and community wellbeing on the outputs of a standard land use planning process which is primarily focused on environmental variables. We consulted regional stakeholders to identify the health issues that have environmental links in the Sacramento, California region and to identify potential indicators and datasets that can be used to assess and track these issues. Marxan planning software was used to identify efficient land use patterns to maximize both ecological conservation and human health outcomes. Outputs from five planning scenarios were compared and contrasted, resulting in a spatially explicit series of tradeoffs across the scenarios. Total area required to meet imputed goals ranged from 10.4% to 13.4% of the total region, showing somewhat less efficiency in meeting biodiversity goals when health outcomes are included. Additionally, we found 4.8% of residential areas had high greening needs, but this varied significantly across the six counties. The work provides an example of how integrative assessment can help inform management decisions or stakeholder negotiations potentially leading to better management of the production landscapes in food systems.

Keywords: conservation planning; human health; Marxan; biodiversity; land use; smart foodsheds

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1. Introduction

Food systems are the full suite of actors, actions, and systems that describe the production, distribution, and consumption of food [1]. They encompass the natural environment in which it is produced as well as social and human systems. As such, they are very complex, and planning for and within them has historically been done in a "siloed" manner. More recently, there have been efforts to move planning in a more holistic direction, at least within portions of food systems.

One example can be found in biodiversity assessments. Systematic conservation planning has been undertaken in many contexts globally for several decades. These efforts generally consist of assessing current status of land use in a planning region, identifying conservation targets, establishing goals for these targets, identifying gaps where regional goals have not been reached, and applying a variety of planning tools to identify effective ways of closing these gaps to meet a full suite of planning goals [2,3]. The systematic nature of this approach has led to more inclusive planning frameworks and away from planning for single features (e.g., species) in many cases.

Nevertheless, these kinds of conservation assessments and plans typically focus solely on ecological needs. They are explicitly designed to account for future conservation of species, ecological communities, and related biological resources. While this approach serves as a potential necessary first step, it often neglects a human element, except insofar as human resource exploitation often being a negative driver of ecological integrity, thereby ignoring many components of integrated regional systems. Where interaction between humans and the non-human environment are explicitly taken into account, it is usually found in the realm of sustainable resource extraction for direct economic benefit for local communities [4].

The most commonly used conservation models, such as Marxan and Zonation, were developed to address the problem of how to identify a portfolio of protected lands that efficiently and effectively protect a specified mix of rare resources on a mixed-use landscape. However, although these methods envision simultaneously maximizing expression of a heterogeneous mix of species or ecological communities, there is nothing in the concept or mathematics that preclude using them for a much richer and more heterogeneous mix of amenities, including, for example, food production, water quality, and rural employment along with environmental and public health outcomes.

Human interactions with and benefits from the environment go beyond resource extraction. The quality of water, air, soil, and food are directly tied to health and dependent on environmental conditions. In addition, there is a growing understanding of more complex ways that ecosystems can impact human health. For example, biodiversity of plants, animals, and microbes is important for preventing the occurrence of zoonotic diseases such as Lyme disease [5] and has even been implicated as a protective factor in asthma, allergies, and other inflammatory diseases [6]. Crop diversity is directly linked to nutrient diversity. In addition, observational studies consistently show that proximity to greenspace is an important independent predictor of good health and longevity, although it is not completely clear what factors mediate these findings [7].

Rates of chronic disease continue to increase around the nation [8]. It has long been recognized by the Centers for Disease Control and Prevention (CDC) that good health status in the United States depends more on how and where we live, work, learn, and play than on access to medical care. These social determinants of health (SDH) play an outsized role in human health [9]. Recent data published in the Journal of the American Medical Association showed that individuals in the wealthiest zip codes live an average of 15 years longer than in the poorest zip codes and that the environment is largely what explains this survival gap [10]. Given this, there is the possibility for communities to improve the physical environment and drastically reduce this disparity.

Despite a widespread acceptance of the role of the environment on health outcomes, health factors are inconsistently integrated into land use planning initiatives. Although potentially toxic exposures are infrequently considered, land use options that are health promoting (such as proximity and access to green space, walkable communities, public transportation, nutrient rich food production, healthy biodiverse soil and farms, and clean water and air) are rarely considered. Furthermore, the true health cost of land use decisions, i.e., the way these decisions translate into medical costs and disability costs, are rarely quantified.

Another cause of the lack of integration often seen in landscape planning lies in relying solely on scientific workflows. There are many kinds of workflows [1], and better integrated planning can potentially be attained through a better workflow integration. In this project, we explicitly linked a scientific workflow with a stakeholder workflow to gain a wider perspective on sustainability issues in the planning region.

We used the Sacramento region of northern California as a test case to explore the explicit linkage of biodiversity conservation with human health outcomes. We used a spatially explicit conservation planning model to explore the outcomes resulting from prioritizing different environmental drivers of human health while achieving the same levels of biodiversity protection across the six-county landscape.

Our working hypothesis in this process was that the inclusion of multiple human health objectives in spatially explicit natural resource planning scenarios would result in a heterogeneous set of outputs. The null hypothesis conversely was that planning for natural resources alone would achieve the same pattern of reserve networks as would scenarios that included health outcomes.

Although it goes beyond our analysis, we further hypothesize that multi-scenario outputs can serve as important sources of information in both decision-making and in stakeholder negotiations in land use planning. While the analysis and tools developed are specific to the Sacramento region, the effort will provide a template for developing an adaptable workflow for application in other regions, with the potential to influence land use planning practice far beyond Sacramento.

2. Materials and Methods

2.1. Study Area

The Sacramento region is comprised of six counties in northern California (Figure 1). The counties include these landscapes: (1) flat, low elevation largely agricultural areas; (2) rolling foothill terrain covered largely with oak woodlands; and (3) high elevation montane areas largely consisting of conifer forests. The largest city in the region is Sacramento, and most of the other population centers are found in the low elevation areas, although several smaller cities are found in the other areas as well.

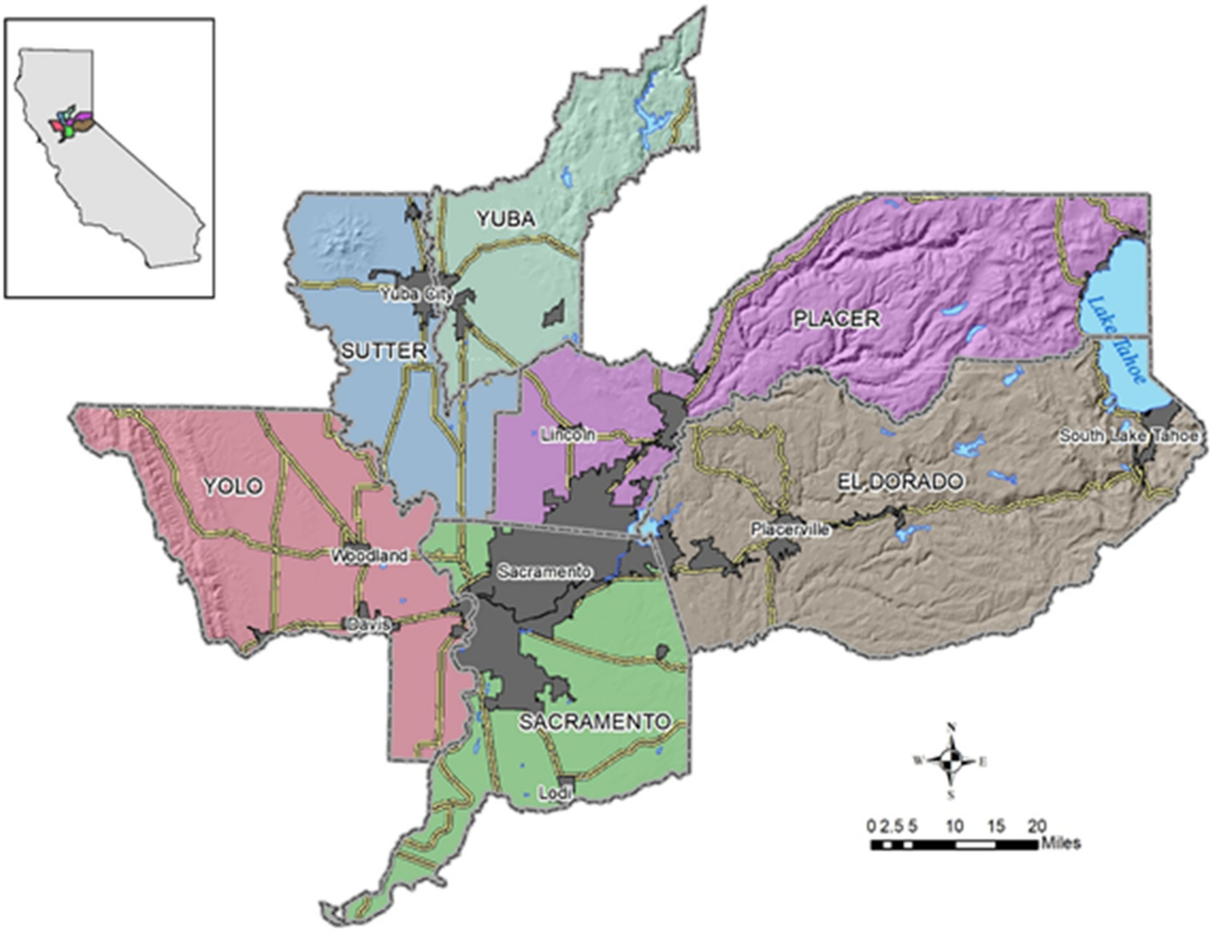

Figure 1. Sacramento region, California. The colors depict the six counties that comprise the region.

The vast majority of the lower elevation areas have been converted from natural to agricultural land cover types, while much of the higher elevation area remains as relatively intact natural habitat and largely in public ownership. California is a global biodiversity hotspot, with many rare, highly endemic species. Efforts are underway throughout the region to protect and restore portions of the landscape for biodiversity preservation.

We selected this region for this project because of its important role in agricultural production, its high biodiversity value, urbanization pressures, and multiple environmental risks to human wellbeing.

2.2. Stakeholder Engagement

The work undertaken through this project was heavily predicated on engagement with regional partners both as resources and to help prioritize and guide the focus of the research. A series of consultations with the natural resource management community and the public health community was held, followed by a joint workshop bringing the two communities together.

2.2.1. Environmental Consultations

As groundwork for this project, the research team consulted with experts from public agencies, conservation organizations, and university faculty most familiar with collecting, hosting, or using regional environmental datasets. We engaged with natural resource experts and conservation practitioners, and particularly those that would have familiarity with, and access to, spatial natural resource data. The project hosted three multi-attendee meetings as well as three single-attendee meetings to assess available natural resource information for the Sacramento region. A total of 19 attendees participated either in person or via phone during this phase. Dozens of new datasets were identified as well as existing data gaps.

To structure the meetings, we used a list of Integrated (broader) and Component (narrower) Issues that our team had developed during previous work [11,12]. The following Integrated environmental priority issues for the Sacramento region were discussed: Air and Climate, Biodiversity, Common Pool Resources, Deforestation, Ecosystem Services, Land and Soil, Protected Areas, Wastes and Pollution, and Water. The process highlighted 81 priority Component Issues (narrower) within these categories and cataloged 71 important datasets linking to the identified issues.

2.2.2. Health Consultations

Drawing from the networks of two extant Sacramento collaborations on health-related planning issues, the "Healthy Sacramento Coalition" sponsored by the Sierra Health Foundation, and the "Building Healthy Communities" initiative sponsored by the California Endowment, the project compiled a total of over 100 regional health-related stakeholders, including: health providers and practitioners, health researchers from both academic institutions and government agencies, regional planners, and advocates focused on range of land use, transportation, housing, and environmental justice issues. Of this comprehensive list of relevant regional stakeholders, project partners selected a targeted list of 24 representative experts for direct one-on-one interviews.

Priority health-related issues identified include access to healthy food (nutrient-dense, fresh), transit-oriented development (urban design)/active transportation, walkable neighborhoods (walking school buses), mental health (depression, isolation, stress), physical health (cardio, diabetes, sedentary lifestyle, hypertension), air quality, unemployment/limited income, lack of greenspace/tree canopy, safety, and wildfires/climate change/greenhouse gas emissions. We selected issues from this list that were most appropriate to assess using spatial analyses. The four selected were: (1) mental and physical health (positive influence: access to greenspace); (2) air quality; (3) lack of greenspace/tree canopy; and (4) wildfires, climate change, and greenhouse gas emissions. (Note: Health consultations took place immediately following a severe fire season in the region, hence there was significant attention on air quality issues during this period.)

2.2.3. Workshop

A subset of the "environmental" stakeholders and "health" stakeholders were jointly convened through a workshop to reflect on these initial rounds of analyses for input on refinement, expansion, and next steps for investigation, with the following stated objectives: (1) update participants on the work done to date; (2) "ground truth" methods and outputs; (3) gather insights on trade-offs among health and environmental priorities; (4) solicit feedback on ways to maximize the usefulness and availability of the work for participants; and (5) identify future steps.

The format included large group presentations and discussions and small group sessions focusing on regional scenarios and priorities. Individuals were also asked to fill out three brief questionnaires to indicate their priorities on the importance of different issues, responses to the methodologies used in the study, and preferences for accessing and communicating data and other project outputs. There was a clear desire by the group to continue engaging with the research and interest in exploring and expanding use of the presented methodologies to include a wide range of additional sustainability issues for the region. Requests for access to linked online mapping and other data were high.

2.2.4. Marxan

Marxan is optimization software designed for use in conservation reserve design [13]. It was originally designed for use in selecting marine reserves and, more generally, in designing spatially explicit conservation reserve networks. It is a widely used conservation planning tool, used globally in a wide variety of reserve planning contexts [14,15], as well as in California [16]. More than 100 peer reviewed papers describe some of the projects in which it was used by scientists or planners in support of conservation decisions.

Marxan works by using a simulated annealing algorithm to explore many configurations of planning units, incrementally moving towards solutions that meet input conservation objectives in "low-cost" ways. "Cost" is defined by the user; it can refer to monetary cost but more generally refers to the suitability of a given planning unit for inclusion in a final conservation network. While it is unlikely that simulated annealing will produce an absolute lowest cost solution, it will identify scenarios that map relatively low cost, or most suitable, solutions to meeting a user's conservation objectives.

Marxan uses three fundamental input tables (files) for an optimization analysis. The first is the "planning units" (PU) table file. This table is a list of all the sites that could potentially be selected for inclusion in a planning process. Typically, these would be land parcels or other regular polygons that comprise the modeled landscape. Each planning unit is given: (1) a unique ID, (2) a "cost" for inclusion in a final conservation network, and (3) a status (i.e., whether eligible to be selected, "locked in" a final Marxan solution, or "locked out" of a solution). Cost scores are used to score the suitability of sites for inclusion in a conservation network. They typically consist of ecological factors, but they can include much more heterogeneous amenities, such as health costs associated with poor nutrition and values of protecting water supplies or recreational access, so long as values can be expressed in compatible units.

The second required input file is the "species" file. This table lists every conservation target in an analysis as well as the goal for inclusion of that target. Typically, these could be numbers of species occurrences, acres of land cover types, etc.

The final input table in Marxan is the "planning unit vs. species" file. This table details the amount of each conservation target present in each planning unit.

Marxan has several parameters that can be adjusted to best capture the conservation goals of the user. Some of the typically used parameters are "runs", "iterations", and the "boundary modifier".

While Marxan is not designed to identify a true lowest cost solution to a given conservation problem, it does generate multiple low-cost solutions. To do this, an input file is created that tells Marxan how many runs to undertake. At the end of each run a set of potential planning units is identified that meets the targeted conservation goals. Generally, Marxan analyses use multiple runs to fully explore the range of potential solutions and to indicate to stakeholders the magnitude of investment likely required to attain a desired level of benefits.

The input file also includes the number of iterations (i.e., combinations of planning units) to assess in the course of each run. The greater the iterations, the closer Marxan's approach to an optimum solution. However, computing time increases as well, so a balance between optimization and computing time is typically sought.

The boundary modifier is a multiplier applied to the total boundary length of the conservation network identified during a run. The higher this modifier is set, the greater the clumping of planning units in the solution. This modifier requires calibrating in every analysis to achieve the desired clumping because it simply acts as a multiplier to other costs.

Marxan generates two types of output tables. The first is the "best" solution, i.e., the single lowest cost set of planning units identified for all the runs. The value is binary, either included in the set or not.

The second output table is the "summed solution" table. This file describes the number of runs in which the planning unit was included as part of a low-cost solution. Here, each planning unit is scored 0 to n, with n equal to the total number of runs Marxan performed. This score can be thought of as an "irreplaceability" metric for the planning units. Those with a higher score are likely more critical in addressing the conservation goals in a low-cost manner, while those with a lower score are generally more substitutable.

We used 10-ha hexagons as the PU. PU comprised of at least 50% urban land cover were classified as "urban" and locked out of the Marxan analysis. PU with their centroid inside an existing conservation area were considered "conserved" and locked into the Marxan solution. All other PU were considered "available" to be included in the Marxan solution. The cost of all planning units was set at 1.0.

Conservation targets selected for the project's Marxan assessments were derived through both previous conservation projects in California and through the natural resource-focused stakeholder process. They included major land cover types, special habitats and ecosystems, important wildlife linkages, important agricultural areas, and groundwater recharge areas. Conservation goals for these targets were determined by the total amount of each target; rarer targets were given a higher goal rate (Table 1). These protection levels were selected to ensure substantially increased protection of each of the conservation targets (i.e., high enough) while simultaneously allowing Marxan room to search the "solution space" in order to identify the most critical target locations within a complementary conservation network (i.e., low enough).

Table 1. Conservation targets and goals used as inputs to Marxan. "Current (%)" indicates the current amount of the target that is currently located in public or private conservation lands in the region. "Goal (%)" refers to the minimum total amount of the target that must be included in the final reserve network.

Type	Target	Current (%)	Goal (%)
Land cover	Alpine dwarf-shrub	93.7	100
	Annual grassland	16.6	25
	Aspen	70.3	100
	Bitterbrush	27.4	100
	Blue oak-foothill pine	18	50
	Blue oak woodland	17.7	50
	Closed-cone pine-cypress	82.8	100
	Coastal oak woodland	5.6	100
	Coastal scrub	18.2	100
	Desert riparian	0	100

Table 1. *Cont.*

Type	Target	Current (%)	Goal (%)
Land cover	Douglas fir	44.9	50
	Eastside pine	43.7	75
	Fresh emergent wetland	64.2	75
	Jeffrey pine	59.4	75
	Juniper	79.5	100
	Lodgepole pine	82.7	90
	Low sage	96.5	100
	Mixed chaparral	47.4	50
	Montane chaparral	80.9	50
	Montane hardwood	39.9	50
	Montane hardwood-conifer	43.6	50
	Montane riparian	76.5	90
	Perennial grassland	50.2	75
	Ponderosa pine	42	50
	Red fir	89.8	90
	Riverine	24.3	50
	Sagebrush	47.4	100
	Saline emergent wetland	93.6	95
	Sierran mixed conifer	67.8	75
	Subalpine conifer	95.9	98
	Valley foothill riparian	24.9	50
	Valley oak woodland	7.3	75
	Wet meadow	73.6	80
	White fir	78.2	80
Corridors	Wildlife corridors	13.8	30
Habitats	Vernal pools—complex	21	50
	Vernal pools—large pool	16.1	75
	Monarch butterfly	24	50
	Critical Habitat—CA red-legged frog	32	50
	Critical Habitat—CA tiger salamander	24	50
	Critical Habitat—Sacramento Orcutt grass	37	50
	Critical Habitat—slender Orcutt grass	6	50
	Critical Habitat—Sierra Nevada yellow-legged frog	85	90
	Critical Habitat—valley elderberry longhorn beetle	89	95
	Critical Habitat—vernal pool fairy shrimp	31	50
	Critical Habitat—vernal pool tadpole shrimp	33	50
	Critical Habitat—yellow-billed cuckoo	82	90
Agriculture	Prime farmland	6.4	25
	Rice	6.8	25
	Priority rangeland	24	50
Other	Groundwater recharge potential	8	25

Test runs were conducted to determine an appropriate boundary modifier score (0.1), where the resulting Marxan outputs would be of typical reserve size. We selected 100 runs at 1 billion iterations.

We developed four scenarios, each accounting for a different aspect of regional public health. The conservation targets and goals as well as model parameters were identical across all four scenarios (and identical with the base run). However, the PU cost scores differed between scenarios, thereby shaping the final reserve network configuration. Costs were determined as follows:

Scenario 1—Access to Open Space

Access to open space has many associated health benefits. In this scenario, a lower cost was given to PU in proximity to existing urban areas in order to favor those areas where possible while meeting the conservation goals. Proximity was assessed by calculating the density of urban land cover pixels within a 3-mile radius moving window. Cost was set by calculating the density of urban land cover pixels using a 3 km moving window. The cost of the planning unit was scaled so that cost = 0.1 for units with 100% urban pixels within them and cost = 1.0 for those with 0% urban pixels.

Scenario 2—Fire Threat

Wildfires can threaten human health through direct injury and mortality as well as through exposure to smoke particulates. In this scenario, a lower cost was assigned to PU with a high modeled fire threat. This approach assumes that future conservation of these lands will prevent new development, thereby reducing the number of regional residents exposed to high fire risk. Cost was calculated by scaling the California Department of Forestry and Fire Protection's statewide Fire Threat model so that high fire threat pixels had cost = 0.1 and low threat had cost = 1.0. Mean scores were then calculated for each planning unit.

Scenario 3—Climate Change Threat

Climate change will likely adversely affect human health through rising temperatures, enhanced wildlife risk, and other environmental effects. We used a climate change exposure model developed by Conservation Biology Institute to represent the regional effects of climate change. The PU costs scores were calculated using Conservation Biology Institute's California Climate Exposure model. Cost scores were scaled so that cost = 0.1 for high exposure pixels and cost = 1.0 for low exposure pixels.

Scenario 4—Pollution risk

Pollution poses a risk to human health, especially for communities that have a lesser capacity to ameliorate the risk. We used a California statewide index that combines pollution levels and social factors as an input to Marxan to steer future conservation areas towards these vulnerable regions. The goals are twofold: (1) provide more open space to disadvantaged communities, and (2) reduce future development within polluted areas. The PU cost scores were calculated using California EPA's EnviroScreen composite score that combines pollution and population characteristics to identify areas of high potential pollution risk. Pollution values were scaled such that high index scores were given values of cost = 0.1 and low values at cost = 1.0.

While the Marxan analyses were explicitly focused on the non-urban working landscapes of the region, there are potential relationships between natural resources and human health outcomes in the urban portions of the region. The stakeholder process served to make apparent the link between access to nature in urban settings and its effects on human health (physical and mental). For example, canopy cover can be effective in alleviating urban heat extremes [17]. This in turn may lead to positive human health outcomes, both physical and mental [18]. The presence of urban canopy has also been shown to positively affect obesity, social cohesion, stress levels, diabetes, and asthma [19,20]. Urban tree canopies have been shown to decrease particulate matter in the air [21]. In addition, native trees, especially valley oaks (*Quercus lobata*) in the Sacramento region [22], host a large number of native animal species. Urban forests also sequester significant carbon thereby potentially playing an important role in climate change mitigation [23]. Strategic plantings of native trees can thus serve multiple purposes.

In this light, we identified locations within the region's urban areas that could be selected for enhancement of the urban tree canopy to benefit human residents as well as the native biota. We developed a Greening Needs Index (GNI) for the subset of the hexagons that consisted of at least 50% urban land cover and were zoned residential under city or county general plans. The index scores were calculated using three metrics:

- EnviroAtlas score (pollution + vulnerable communities, value = 0–1). (This US EPA tool is available at: https://www.epa.gov/enviroatlas (accessed on 19 June 2023)
- Existing density of tree canopies (scored 0–1, with 0 = 100% tree canopy and 1 = 0% canopy)
- Distance to existing public open space (scored 0–1, with 0 = 0.0 km to existing protected open space and 1 = 1.0 km or greater distance)

The GNI identifies areas that have pollution issues, are in disadvantaged communities, have little existing tree canopy, and are at a distance from accessible open space. A final value (0.0–1.0) was calculated by multiplying the three input variable scores.

3. Results

3.1. Marxan Outputs

Each planning unit was given a final Marxan score ranging from 0–100 based on the number of runs (out of 100) in which the planning unit was selected as part of the resulting conservation network. Higher scores represent planning units that have a higher irreplaceability for achieving an efficient solution to meeting all the input goals. These are represented in the red colors on the output map (Figures 2 and 3).

Planning units outside of currently protected areas that received irreplaceability scores of at least 90 can be considered critical for achieving conservation goals efficiently while adhering to the parameters of a given scenario. Table 2 shows the total percentage of each county as well as the full region that received these scores across each of the five scenarios. The greater number of planning units required, especially in scenarios 2 and 3, indicate that incorporating health outcomes can mean that biodiversity goals are met in less efficient ways than if they are the sole scenario parameter. Conversely, there is only a 0.1% difference in total area between the base scenario and Scenario 1 (public access) suggesting that this public health benefit could be achieved with very little loss of conservation area efficiency.

Table 2. Percentage of each county currently unprotected with a Marxan score of at least 90 for that scenario. The mean percentage selected is shown in the last column. The total for the full study region is shown in the last row.

County	0-Base	1-Urban	2-Fire	3-Climate	4-Pollution	Mean
El Dorado	9.7	9.7	16.3	12.2	9.9	11.6
Placer	9.0	9.6	11.6	16.9	8.7	11.2
Sacramento	10.9	11.5	9.4	9.4	10.8	10.4
Sutter	9.9	9.4	10.9	13.8	14.5	11.7
Yolo	9.0	8.5	8.9	7.1	8.5	8.4
Yuba	16.1	16.4	20.7	22.9	21.0	19.4
All Counties	10.4	10.5	13.1	13.4	11.2	

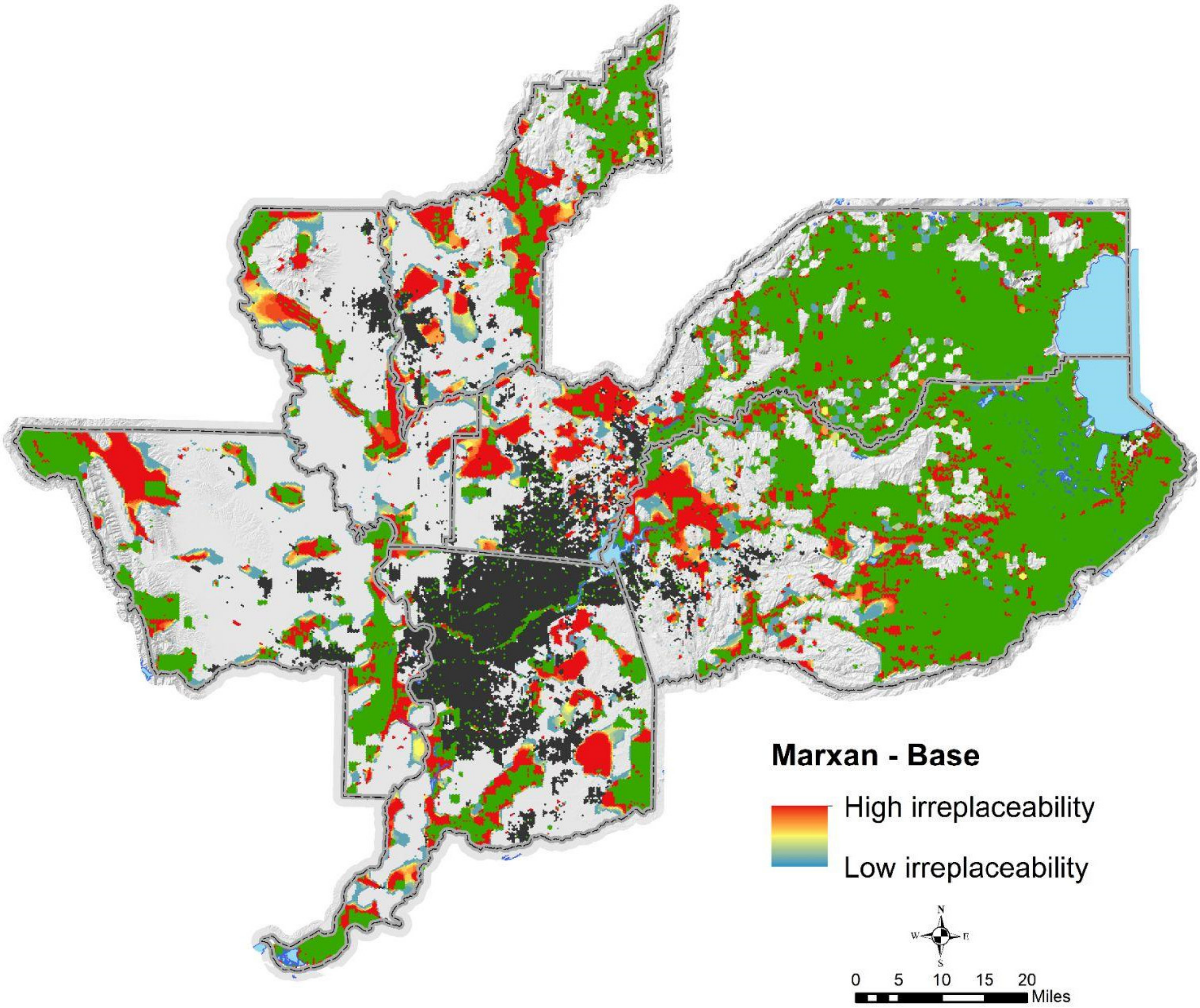

Figure 2. Marxan outputs for the base scenario. Areas in red are those receiving high Marxan scores and are therefore required to achieve the input conservation goals in an efficient and effective manner. Areas in green are existing public and/or conservation lands.

Changes in reserve networks across scenarios are not distributed equally within the study region (Table 2). While counties such as Sacramento and Yolo see relatively modest area differences between scenarios, other counties see a larger change in total reserve area. For example, in Placer County, highly irreplaceable areas for achieving climate threat goals in Scenario 3 are 8.2% greater than those areas for meeting pollution exposure goals in Scenario 4. Similarly, El Dorado County has 6.6% more irreplaceable areas for fire threat abatement (Scenario 2) than for either the Base Scenario or Scenario 1 (public access). Across the region, 7.8% of the total area was identified as highly irreplaceable across all five scenarios.

After generating the scenario outputs, we conducted pairwise comparisons between each of the five scenarios (Figures 4 and 5) by subtracting one set of irreplaceability scores from the other, creating a scale running −100 to +100. PU with scores at either end of this scale can be considered very important conservation areas in one scenario but not the other. PU with a score of zero had the same irreplaceability scores across the scenarios. These planning units may or may not have been selected in the scenarios (for example planning units with matching scores of 100 received the same value as those with scores of 0). In Figures 4 and 5, planning units in yellow received Marxan scores in both scenarios greater than zero. Uncolored PU received irreplaceability scores of 0 in both scenarios.

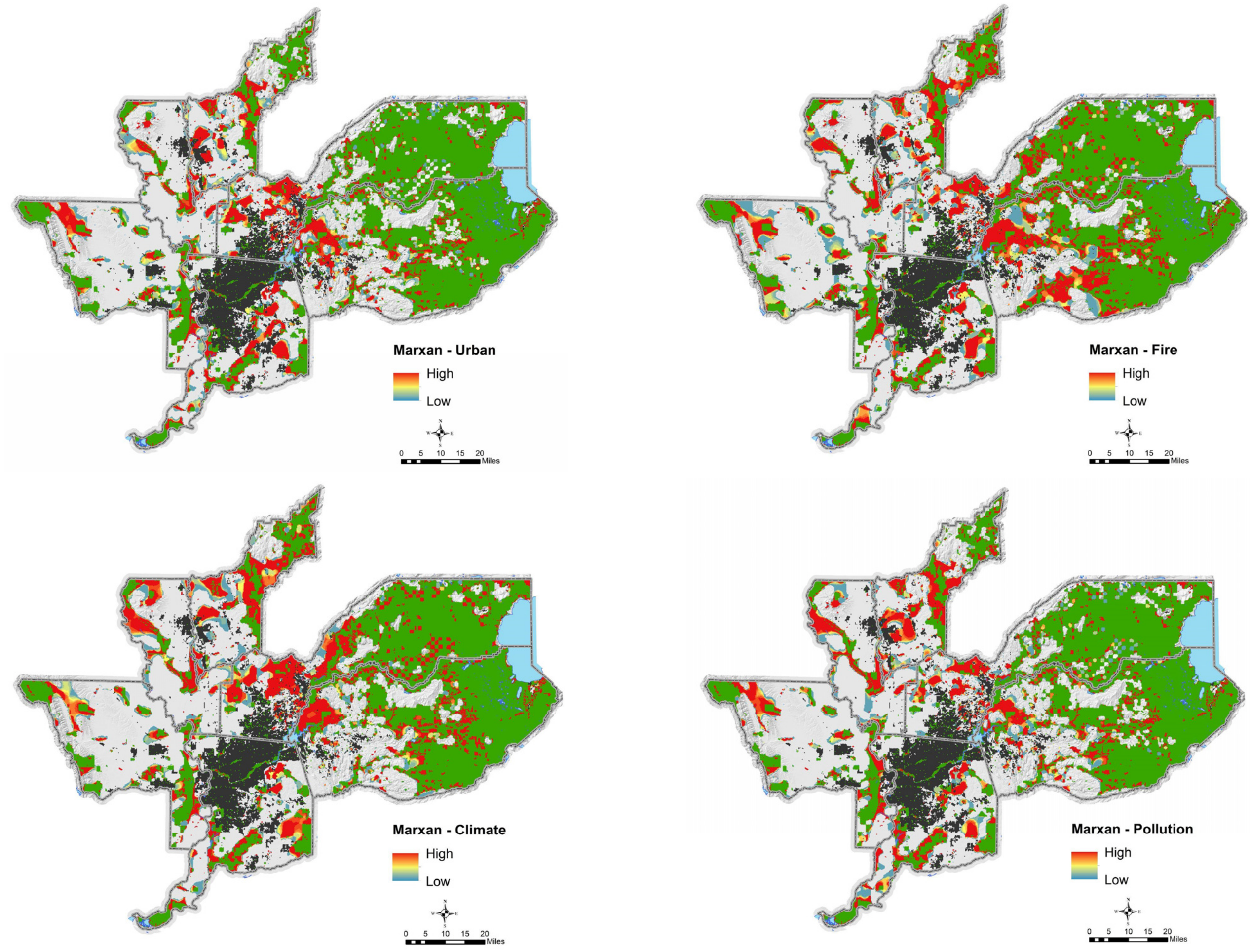

Figure 3. Marxan outputs from the four scenarios. Areas in red are those receiving high Marxan scores and are therefore required to achieve the input conservation goals in an efficient and effective manner. Areas in green are existing public and/or conservation lands.

Calculated differences between each pair of scenarios are shown in Table 3. The percentage of the total study region was calculated that was selected in both scenarios but had an irreplaceability score differential of at least ±90. We see that in some cases irreplaceable reserve areas changed very little between scenarios, such as between the Scenarios 0 and 1 (0.06% difference) and Scenarios 0 and 4 (0.5%). However, there were significantly larger differences in irreplaceable areas between Scenarios 1 and 2 (3.23%) and Scenarios 2 and 4 (3.13%).

Table 3. Comparisons between each unique pair of the five modeled scenarios. "Diff %" refers to the percentage of the total area of the study region in which the difference between Marxan scores was equal to or greater than ±90.

Scenario A	Scenario B	Diff %
1—Urban	0—Base	0.06
2—Fire	0—Base	2.92
3—Climate	0—Base	2.73
4—Pollution	0—Base	0.50
1—Urban	4—Pollution	0.81
2—Fire	4—Pollution	3.13
3—Climate	4—Pollution	2.63
1—Urban	2—Fire	3.23
1—Urban	3—Climate	3.10
2—Fire	3—Climate	1.92

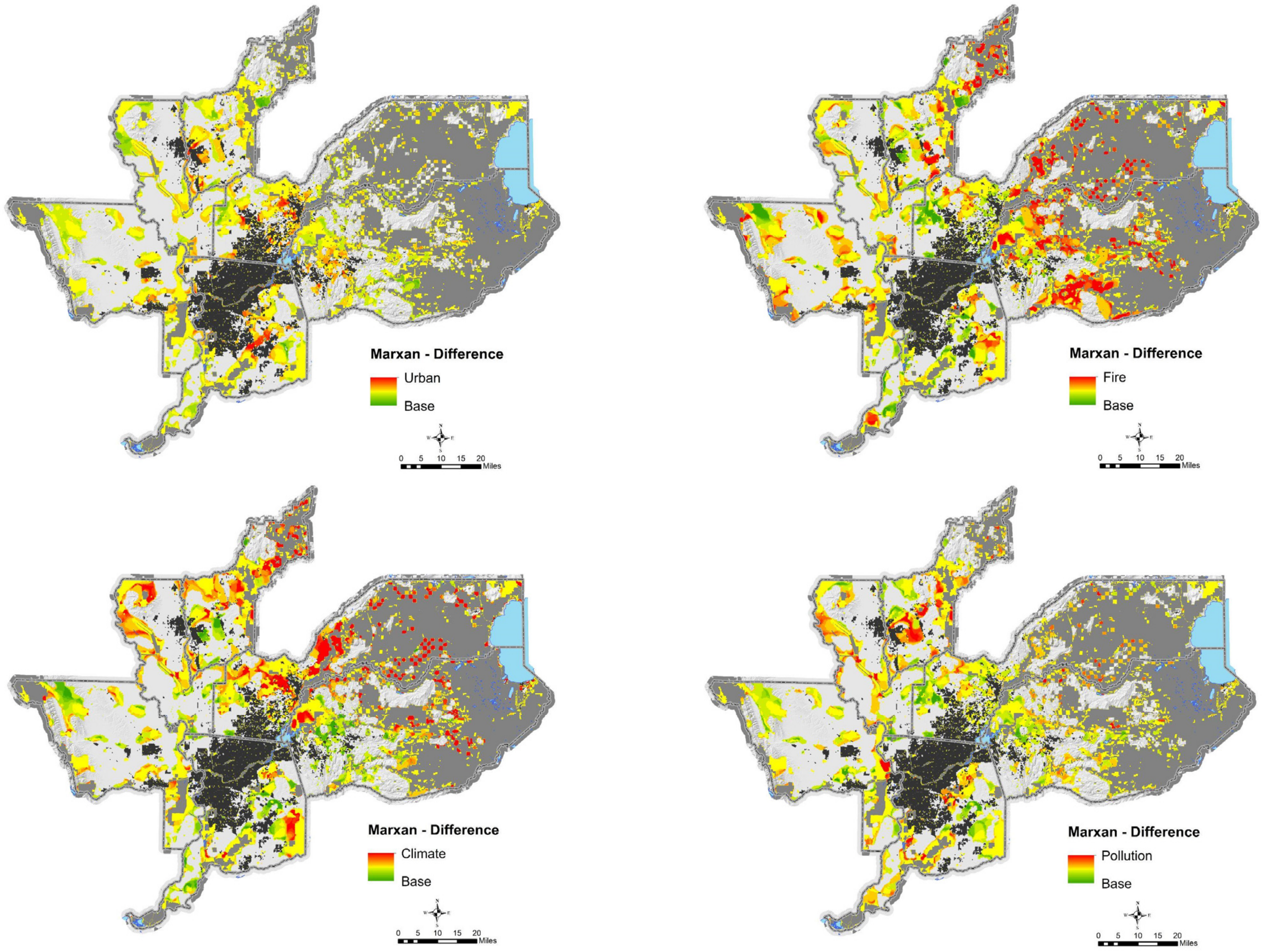

Figure 4. Pairwise comparisons between the four scenarios and the base case. Areas in red were selected in the scenarios but not the base case, while green in the base case and not the scenarios. Yellow denotes equivalent scores in both.

3.2. Urban Greening

Mean GNI varied across the region from 0.07 in El Dorado County to 0.33 in Yuba County (Table 4). The mean across the region was 0.16. High urban greening needs (GNI $\geq$ 0.5) varied across the six counties. While typically wealthier, suburban residential areas in El Dorado County had no areas of high GNI, the more agriculturally focused counties of Yuba and Sutter exhibited high GNI in 27.4% and 11.5% of their residential areas, respectively. While Sacramento County was roughly average for both mean GNI and percentage of high GNI, it had the largest total area of high GNI (2910 ha). This is not surprising given the large total area of residential land use in the county. The heaviest concentrations of high GNI were in the Sacramento and Marysville urban areas (Figure 6). Using aerial imagery, it is noticeable that many high need areas correspond to existing mobile home parks. Figure 7 is an example of one such location in south Sacramento.

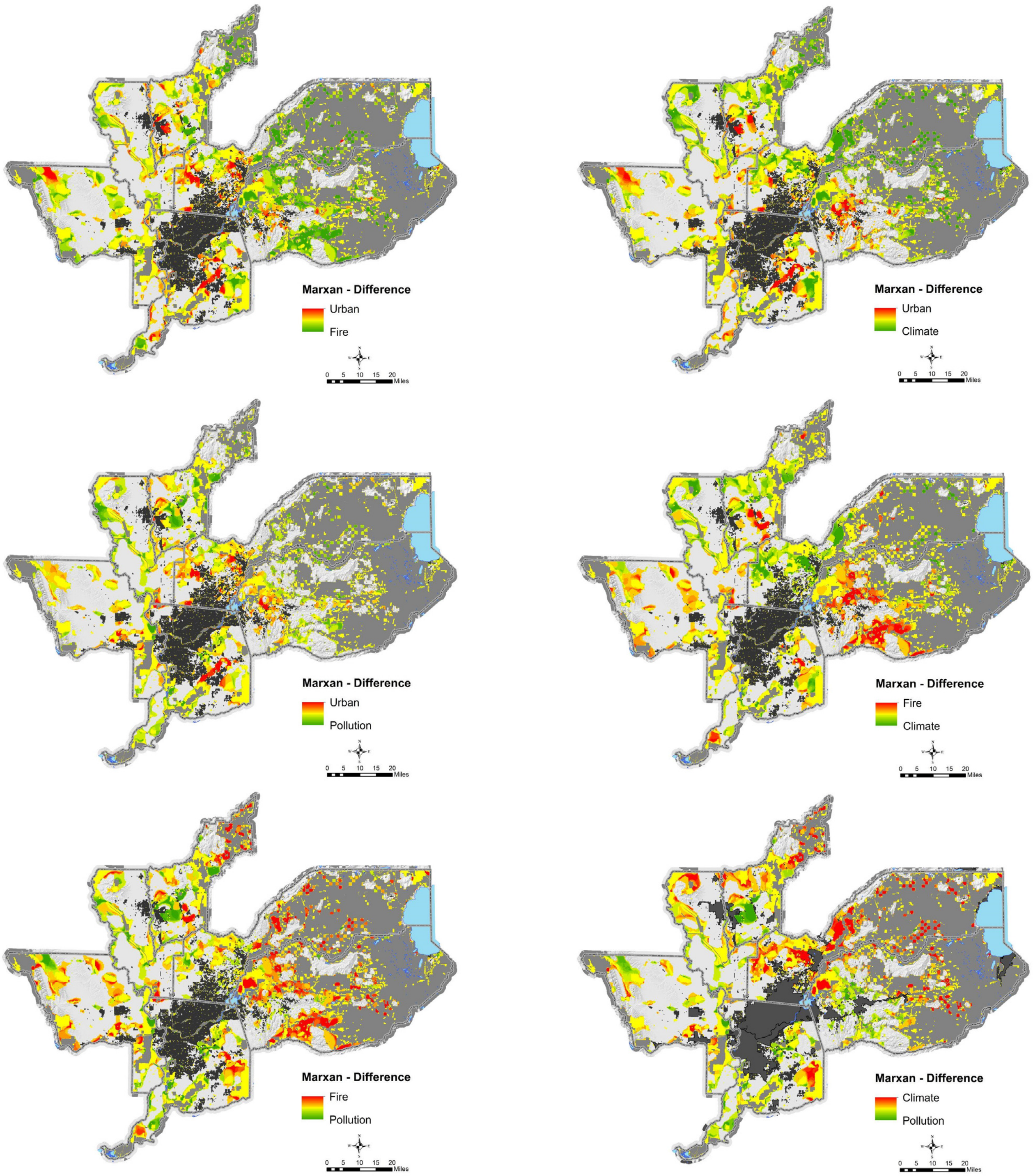

Figure 5. Pairwise comparisons between each of the four Marxan scenarios. Areas in red or green were critically important in the scenario indicated in the legend but not in the other scenario.

Table 4. Urban greening needs for each county. "Res Area (ha)" denotes the total hectares of residential area. "Mean GNI" is the mean Greening Needs Index score. "High (ha)" is the total hectares of residential area scoring a minimum GNI of 0.5, while "High (%)" is the percent of the residential area with these high scores.

County	Res Area (ha)	Mean GNI	High (ha)	High (%)
El Dorado	10,240	0.07	0	0.0
Placer	13,490	0.08	30	0.2
Sacramento	57,790	0.18	2910	5.0
Sutter	4100	0.29	470	11.5
Yolo	7030	0.13	160	2.3
Yuba	4050	0.33	1110	27.4
All Counties	96,700	0.16	4680	4.8

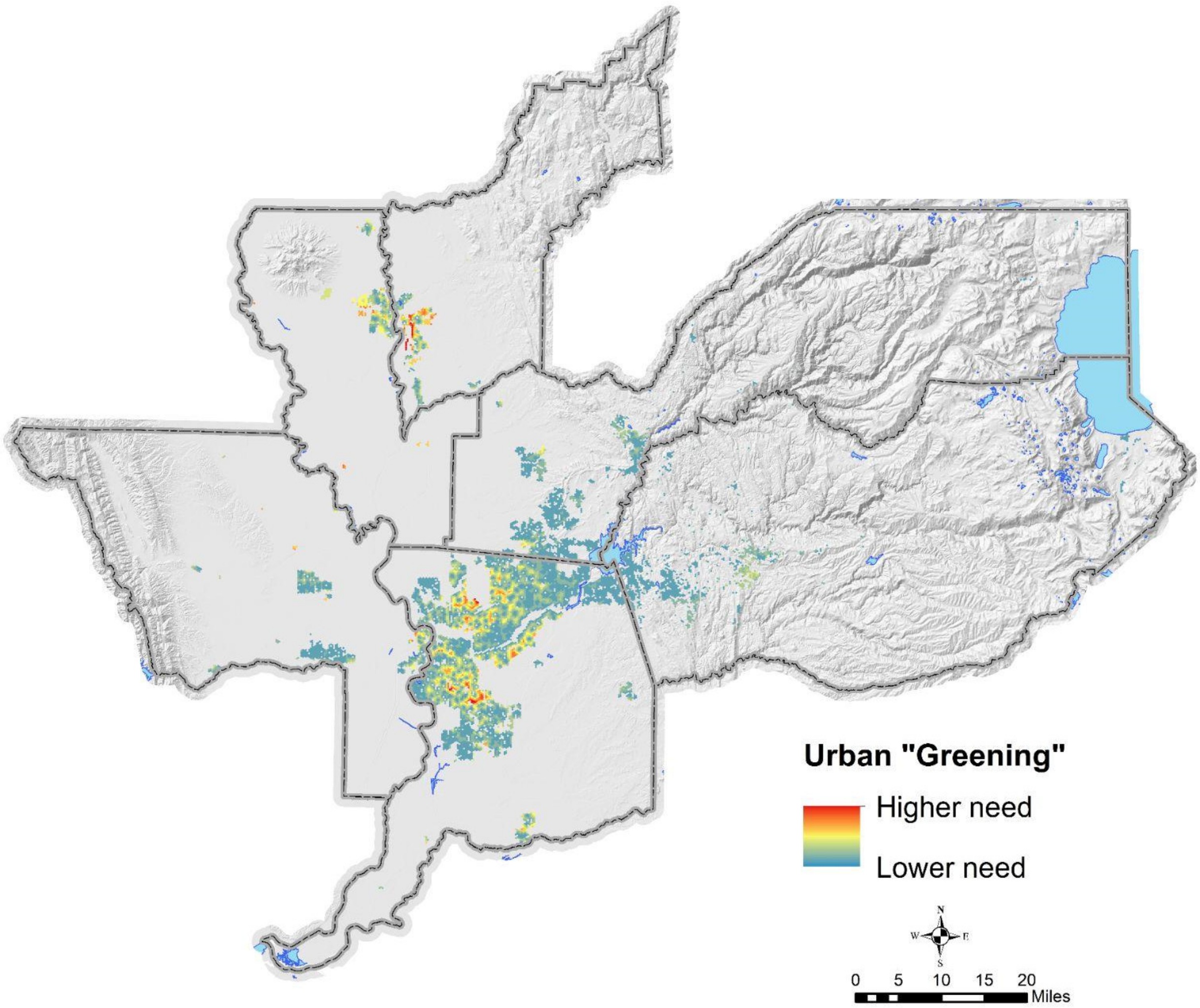

Figure 6. GNI scores for the study area. These scores are calculated through a combination of measured pollution, socio-economic conditions, density of tree canopy, and distance to public open space.

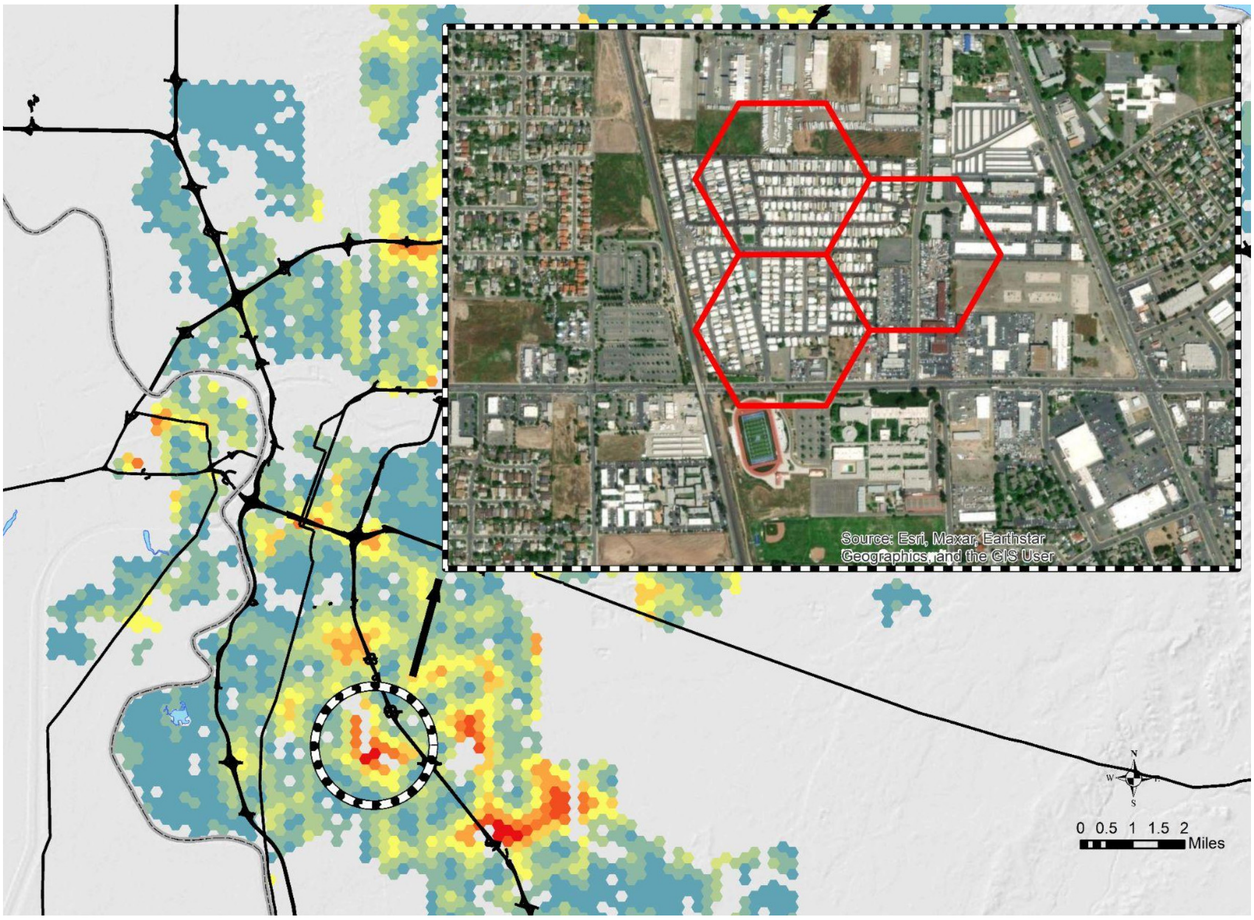

Figure 7. Example of an area in Sacramento with a high GNI score. Note the lack of trees and parks in the vicinity of the trailer park community. The highlighted hexagons are three of the planning units used in the analysis.

4. Discussion

The entire process required linking a stakeholder workflow and a scientific workflow to create a robust sustainability assessment workflow [1]. While the core team was able to bring a starting set of important issues and data into an analytical framework, critical new details were revealed through the stakeholder meetings with the environmental and health community and included as key features in the regional assessment. A subsequent meeting to present our preliminary results and receive feedback included both communities leading to uncommon interactions between usually siloed groups. We believe that this hybrid approach is important in addressing complex problems with a wide set of stakeholders and a diverse set of natural and human systems.

Typically, spatially explicit conservation planning will produce a single land use plan to meet multiple regional objectives. Our approach was to produce multiple outputs based on scenarios developed to express different management goals to better assess the trade-offs inherent in multi-objective planning. This approach will give stakeholders in the region better information on how the choice of priorities can shift optimal land use management patterns. We anticipate that this information will prove useful in support of regional negotiation, rather than a more typical decision support approach.

The increase in total area needed to meet conservation goals from 10.4% to 13.4% as well as the differences shown in Table 3 provide evidence that our hypothesis was correct: adding human health concerns affects the spatial pattern of potential conservation areas. However, the relatively minor effects shown in the contrast between the base case and the urban access scenario suggest that some access needs could be addressed with a relatively low cost in overall reserve network efficiency.

The inverse of trade-off identification is also true here. Planning units selected as important across all the scenarios can be considered "no regret" areas in that they contribute to meeting all the input sets of conservation and health goals. In this analysis, we found the majority of important potential conservation land to belong in this category, totaling 7.8% of the total region. We believe that the smaller areas of disagreement between the scenarios will lead to a more focused set of negotiations and/or decisions that might be required for integrated planning in the region.

Integration of heterogeneous management goals in food systems can be realized at the field level as well as the larger regional scale of these analyses. For example, freshwater wetlands have been largely converted to other human uses (primarily agriculture) in California's Central Valley over the past 150 years [16]. However, over the past several decades many farmers have begun managing flooded rice fields for the benefit of migratory waterfowl [24]. More recently, research has shown that juvenile salmon can also benefit from access to flooded rice fields, greatly increasing the likelihood of survival during migration to the Pacific Ocean [25]. These examples of working landscapes used as proxy natural habitat provide evidence of the multi-benefit potential of adopting a more integrative food systems approach to landscape planning and management.

There are also opportunities for meeting multiple sustainability goals inside the urban perimeter. We identified 4.8% of the total residential area in the region that could dramatically benefit from urban greening and the addition of open space. Targeted intervention in these areas could lead to substantial positive impacts to human wellbeing in the region, especially in the disadvantaged communities identified by the GNI analysis. This could potentially also serve as a source of local food production. Diehl and Kaur (2021) [26] make the case that urban agriculture can help ease increasing competition for rural production. Posivakova et al. (2019) [27] show that urban biodiversity can be improved through agricultural production areas.

Issues included in the analyses will also require further attention to better represent their impact on Californian systems. For example, while the wildfire threat was included as the basis of one of the land use scenarios, this ecological process requires a much more detailed analysis to fully integrate its many aspects within the framework described here. The recent fire seasons in California have been unprecedented in scope and have revealed a number of ways in which wildfire can interface with some of the themes we have developed here. For example, there are major health implications regionally with fires of the magnitude seen over the past four months. In addition, there will likely be impacts on biodiversity, water supply, food systems, and urban development, for example. Future work is needed to better understand these linkages.

The analyses presented here are not meant to be an exhaustive study of human health, ecosystem services, and the sustainability of the Sacramento region. Rather, it was designed to demonstrate an approach that enables the integration of stakeholder-identified information across many disciplines that can provide support for difficult, complicated negotiations where there is not likely to be a single, optimal solution, or even a consensus on what such a solution might look like. The goal of the work presented here is to help make more transparent the tradeoffs inherent in regional sustainability strategies, including regional food system sustainability, rather than to provide a single solution. Future work can use the structures we have developed to link more sustainability themes to better capture the complexity of real-world regions and provide clearer road maps to a more sustainable world and greater human wellbeing.

This work demonstrates the feasibility of using a land-use portfolio mapping tool that to date has been applied almost entirely to biodiversity-conservation studies and to apply it instead to a much wider range of impacts and amenities important to the impacted communities in the greater Sacramento region, and to show that the approach can be persuasive to a range of cross-disciplinary experts and policy analysts.

Integrative efforts such as those proposed here are being seen as increasingly necessary as our global society grapples with complex environmental issues. Lengnick et al. (2015) [28] make the case that developing integrated metropolitan foodsheds can help address climate change risks.

We believe that the complexity of real-world food systems requires an approach such as that taken here. Linking stakeholder and scientific workflows [1] brings an integration that helps provide a wider lens on important considerations within an assessment process. Existing tools such as Marxan can help integrate them into a single assessment framework. Decisions and negotiations can then be made with greater transparency brought to bear on evaluating the difficult trade-offs in meeting multiple goals within a single food systems landscape.

5. Conclusions

Systematic conservation planning typically focuses on meeting multiple biodiversity targets in a planning area. We show here that it can also explicitly include public health benefits. However, planning for these health benefits may require making trade-offs. We chose to link a stakeholder workflow with a scientific workflow to develop a series of planning scenarios that can help make these trade-offs explicit when undertaking comprehensive regional land use planning. These scenarios can help support negotiations among stakeholders when faced with meeting diverse goals in complex working landscapes.

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