A Framework for Considering the Carbon and Health Co-Benefits of Afforestation and Avoided Forest Conversion

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Abstract

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Ecosystem services frequently overlap. Natural climate solutions (NCS) can significantly contribute to carbon dioxide equivalent (CO_2e) emissions reduction goals by increasing carbon storage and preventing CO_2e emissions from forests, wetlands, grasslands, and agricultural lands. Implementation of certain NCS, particularly afforestation and avoided forest conversion, can also provide co-benefits that support human health. However, co-benefit analyses of NCS pathways are rare, which can lead to an underestimation of the value of these NCS pathways and the development of land management plans that overlook opportunities to make progress across multiple objectives. Here, we begin to address this gap by developing a framework for prioritizing areas on the landscape to achieve two management objectives: (1) maintain or increase the capacity to sequester carbon, and (2) reduce adverse human health outcomes through exposure to green space. Using the Puget Sound region as a case study, we operationalize the

framework and explore the benefits for human health disparities and carbon storage, explicitly considering co-benefits when developing implementation plans for NCS. Our analysis revealed that census tracts in less developed areas in the Puget Sound region are relatively high priority for maintaining existing carbon storage, and the same is true of the spatial distribution of the priority of census tracts for maintaining existing carbon storage and simultaneously supporting human health. Conversely, census tracts in and around metropolitan areas in the Puget Sound region are relatively high priority for augmenting carbon sequestration through afforestation, supporting human health, and augmenting carbon sequestration while simultaneously supporting human health. Our analyses highlight that varying the objectives of management actions can generate very different spatial patterns of places where management should be prioritized, and these divergent spatial patterns impact the ability of management actions to achieve specific outcomes.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has warned that global warming exceeding 1.5 °C above pre-industrial levels will result in additional long-term changes in the climate system and increase climate-related risks to socio-ecological systems (Masson-Delmotte et al., 2019). To prevent warming above this threshold, net greenhouse gas (GHG) emissions must be reduced globally by 50% by 2030 and to net zero by 2050 (Masson-Delmotte et al., 2019). Reducing GHG emissions at this pace and scale requires significant reductions by top emitters, including the transportation, built environment, energy, and agricultural sectors (Richter et al., 2008). Natural climate solutions (NCS), or changes in land management, ecosystem restoration, and conservation practices to prioritize carbon storage, can also significantly contribute to emissions reduction goals by increasing carbon storage and preventing carbon dioxide equivalent (CO_2e) emissions from forests, wetlands, grasslands, and agricultural lands (Cameron et al., 2017; Fargione et al., 2018; Graves et al., 2020; Griscom et al., 2017; Robertson et al., 2021).

The potential of NCS to contribute significantly to global (Griscom et al., 2017), national (Fargione et al., 2018), and regional (Cameron et al., 2017; Graves et al., 2020; Robertson et al., 2021) CO_2e emissions reduction goals is well established. At the scale of the globe, Griscom and colleagues (2017) estimated that, even when constrained by the need to ensure a secure food supply and conserve biodiversity, the maximum mitigation potential of 20 NCS pathways (e.g., afforestation, avoided forest conversion, fire management, nutrient management, coastal restoration) is 23.8 billion metric tons of CO_2e per year. They argued that, if deployed by 2017, these 20 pathways could mitigate over one third of the GHG emissions needed to keep global warming below 2 °C by 2030 (Griscom et al., 2017). Similarly, at the scale of the United States, Fargione and colleagues (2018) found that the 21 NCS approaches they explored have a mitigation potential of approximately 1.2 billion metric tons of CO_2e per year, the equivalent of 21% of U.S. net annual emissions in 2018. Regional analyses conducted in Washington (Robertson et al., 2021), Oregon (Graves et al., 2020), and California (Cameron et al., 2017) also showed that NCS have the potential to contribute significantly to carbon goals in those states.

Compared to other NCS pathways, afforestation (i.e., the act of establishing a forest or stand of trees by planting trees in areas that have not recently had trees) and avoided forest conversion (i.e., the act of preventing the conversion of forests to non-forest uses by permanently dedicating land to continuous forest cover and maintaining or increasing stocking levels) generally have some of the highest capacities to increase carbon storage and prevent CO_2e emissions (Cameron et al., 2017; Fargione et al., 2018; Graves et al., 2020; Griscom et al., 2017; Robertson et al., 2021). Globally, afforestation has the potential to remove up to 10 billion metric tons of CO_2e annually, and avoided forest conversion has the potential to remove up to 3.5 billion metric tons of CO_2e annually (Griscom et al., 2017). For comparison, natural forest management, the NCS with the third highest global mitigation potential, can only feasibly remove up to 1.5 billion metric tons of CO_2e from the atmosphere annually (Griscom et al., 2017). Of the NCS that can be deployed in the United States, afforestation has the highest maximum mitigation potential (300 million metric tons of CO_2e annually) and avoided forest conversion has the third highest maximum mitigation potential (40 million metric tons of CO_2e annually). While the potential for afforestation and avoided forest conversion to mitigate carbon varies regionally and across landscapes, it is clear that these NCS pathways can be important tools in the effort to reduce GHG emissions.

In addition to contributing to carbon reduction goals by reducing GHG emissions and increasing carbon storage, deployment of NCS is associated with numerous co-benefits (Colléony & Shwartz, 2019; Gómez-Baggethun & Barton, 2013; Langemeyer, 2016). For example, the trees and forests that are created through restoration of forests and maintained by avoiding the conversion of forests to non-forest used support biodiversity (Ives et al., 2016); purify water, air, and soil (Wei et al., 2021); provide opportunities for recreation (Wen et al., 2018), and safeguard Indigenous food sovereignty and cultural practices (Settee & Shukla, 2020). Importantly, the green space that is maintained and created by these NCS also supports human health (Fong et al., 2018; Frumkin et al., 2017; James et al., 2015; Wolf, 2020). For example, trees from afforestation can reduce air and surface temperatures in urban areas, lessening urban heat islands and decreasing the health risks of extreme heat events (dos Santos et al., 2017). Also, urban forests can improve air quality and are associated with reduced respiratory ailments, such as asthma (Nowak et al., 2018). Finally, natural environments, like forests, can improve human mood states (Hartig et al., 1991, 2003; Laumann et al., 2003; Morita et al., 2007; Ulrich et al., 1991) as well as concentration and performance (Hartig et al., 1991, 2003; Laumann et al., 2003; van den Berg et al., 2003).

As NCS pathways are considered and implemented, they are often evaluated using cost-benefit framing (Griscom et al., 2017, 2020; Hawken, 2017; Neumann & Hack, 2022). Thus, it is critical to consider the full suite of benefits an NCS pathway confers. Carefully considering the health co-benefits of afforestation and avoided forest conversion is particularly important for many reasons. First, doing so enables decision-makers to account for substantial and well documented reductions in medical expenses associated with urban green spaces (Choumert & Salanié, 2008) while assessing the costs and benefits of deployment of these NCS. Furthermore, considering the health co-benefits of afforestation and avoided forest conversion can increase the immediacy and locality of the benefits of these NCS pathways (Romanello et al., 2021), thereby appealing to policymakers and other decision-makers that are motivated by the immediate public health concerns of the communities in their jurisdiction but may be relatively unmotivated by the need to address the climate crisis. As such, considering the health co-benefits of afforestation and avoided forest conversion can garner more social and political support for the implementation of these NCS pathways (Romanello et al., 2021).

Because the carbon (Cameron et al., 2017; Fargione et al., 2018; Graves et al., 2020; Robertson et al., 2021) and health (Akpinar, 2014; Hansen et al., 2017) co-benefits of afforestation and avoided forest conversion vary spatially, planning efforts ought to explore opportunities across the landscape where both carbon and health co-benefit objectives might be addressed. By understanding the geographic pattern of the social-ecological co-benefits of NCS implementation, policymakers, natural resource managers, urban planners, and other decision-makers may be better prepared to (1) compare cost-benefit ratios of implementation at locations, (2) ensure equitable distribution of costs and benefits, and (3) assess of the social and political feasibility of implementation of different NCS strategies (Bustamante et al., 2014; Klinsky et al., 2017; Soto-Navarro et al., 2020).

Because funding for implementation of NCS pathways like afforestation and avoided forest conversion is limited (Buchner et al., 2015) and not all sites have sites have the same potential to provide carbon benefits (Cameron et al., 2017; Fargione et al., 2018; Graves et al., 2020; Robertson et al., 2021) or health (Akpinar, 2014; Hansen et al., 2017), planning efforts also ought to prioritize potential sites for implementation. Prioritization is particularly important in areas like the Puget Sound region of Washington, USA, where land is relatively expensive (Overby et al., 2022), demand to convert natural areas to non-forested uses is high in some areas (Robertson et al., 2021), and opportunities to re-green developed areas are often not politically or financially feasible (Watterson, 1993).

A process recognizing the diverse priorities of policymakers (Alarcon-Rodriguez et al., 2010) could be used to support strategic decision-making, as it could identify solutions that make the most effective use of limited resources. When objectives conflict, for example, multi-criteria decision support systems can provide direct support for decision-makers. Likewise, similar optimization methods (Duan et al., 2016; Giacomoni & Joseph, 2017; Higgins et al., 2008; Raei et al., 2019) can be useful when optimal solutions exist, but planners instead need information regarding how to start the decision-making process. Because afforestation and avoided forest conversion produce many co-benefits, prioritizing for multiple objectives may be particularly useful when evaluating implementation of these NCS pathways. Importantly, multi-objective approaches could also allow for the inclusion of equity and justice as explicit objectives, thereby allowing their transparent inclusion in multi-objective decision-making processes (Hoover et al., 2021).

Although it is important to consider co-benefits of NCS like afforestation and avoided forest conversion, co-benefit analyses of NCS pathways are rare. This can lead to an underestimation of the value of these NCS pathways, and the development of land management plans that overlook opportunities to make progress across multiple objectives. Here, we begin to address this gap by exploring the consequences of implementing NCS spatial planning without explicitly considering co-benefits. Specifically, we develop a framework for prioritizing areas on the landscape to achieve two management objectives: (1) maintain or increase the capacity to sequester and store carbon, and (2) reduce adverse human health outcomes through exposure to green space. Our framework establishes a methodology for creating three distinct single-objective prioritization schemes for carbon, afforestation, and health, which serve as the basis for developing two multi-objective prioritization schemes for carbon and health as well as afforestation and health.

Using the Puget Sound region as a case study, we operationalize the framework and explore the benefits for human health disparities and carbon of explicitly considering co-benefits when developing implementation plans for NCS. Specifically, we investigate how the priority of census tracts under different prioritization schemes is correlated with (1) impervious surface cover, (2) population density, and (3) the demographic composition of those who would benefit from management actions.

Methodology

Study Setting

We focused on the U.S. portion of the Puget Sound Drainage Basin (Figure 1), which is approximately 41,500 km^2 and includes the Puget Sound, the largest marine estuary by volume in the United States (*Vision 2050: A Plan for the Central Puget Sound Region*, 2020). Prior to development, terrestrial ecosystems in the region were dominated by western red cedar, western hemlock, and Douglas fir in the lowlands as well as mixed stands of Douglas fir, Garry oak, and Pacific dogwood at relatively higher elevations (Franklin & Dyrness, 1973). Today, impervious surfaces have replaced forests in many of the cities and metropolitan areas in the central portion of the region (Alberti et al., 2004; Voisin et al., 2023). In less developed areas, tree cover and other forms of green space are generally still abundant, although conversion to agricultural land is common (Voisin et al., 2023).

Figure 1. U.S. portion of the Puget Sound Drainage Basin shown in dark grey. When operationalizing our framework, we used this region as a case study. The region is approximately 41,500 km^2 and includes the Puget Sound, the largest marine estuary by volume in the United States.

The Puget Sound region occupies a portion of the ancestral lands of the Coast Salish peoples and is currently home to nearly 4.3 million people, approximately 40% of whom identify as People of Color (*Vision 2050: A Plan for the Central Puget Sound Region*, 2020). Population and economic growth in the region have been rapid in recent decades and are projected to continue to increase (*Vision 2050: A Plan for the Central Puget Sound Region*, 2020). By 2050, regional authorities expect the population in the region to exceed 5.8 million and be older and more demographically diverse than at present (*Vision 2050: A Plan for the Central Puget Sound Region*, 2020). Over the same period of time, job opportunities in the Puget Sound region are expected to increase from roughly 2.3 million (at present) to 3.4 million (*Vision 2050: A Plan for the Central Puget Sound Region*, 2020). Although urban sprawl has been somewhat curtailed over the last decade, the region is still becoming increasingly urbanized as human populations grow and economic development continues (Voisin et al., 2023). Through the process of urban development, green spaces are often converted to residential or commercial buildings and related impervious surfaces, such as roofs and buildings, roads, parking lots, and sidewalks (Voisin et al., 2023).

Overview of Approach

In this thesis, we develop a framework for prioritizing locations to achieve two complementary management objectives: (1) maintaining or increasing the capacity to sequester carbon in trees and other biomass, and (2) reducing adverse human health outcomes through exposure to green space. Our general approach was to first develop an understanding of the places within an urbanizing geography where the greatest amount of carbon could be sequestered by preventing the conversion of forests to urban land cover or by greening existing urban landscapes. We then examined places with the greatest potential to contribute positively to human health by preserving or increasing contact with green spaces. Our overall workflow is illustrated in Figure 2.

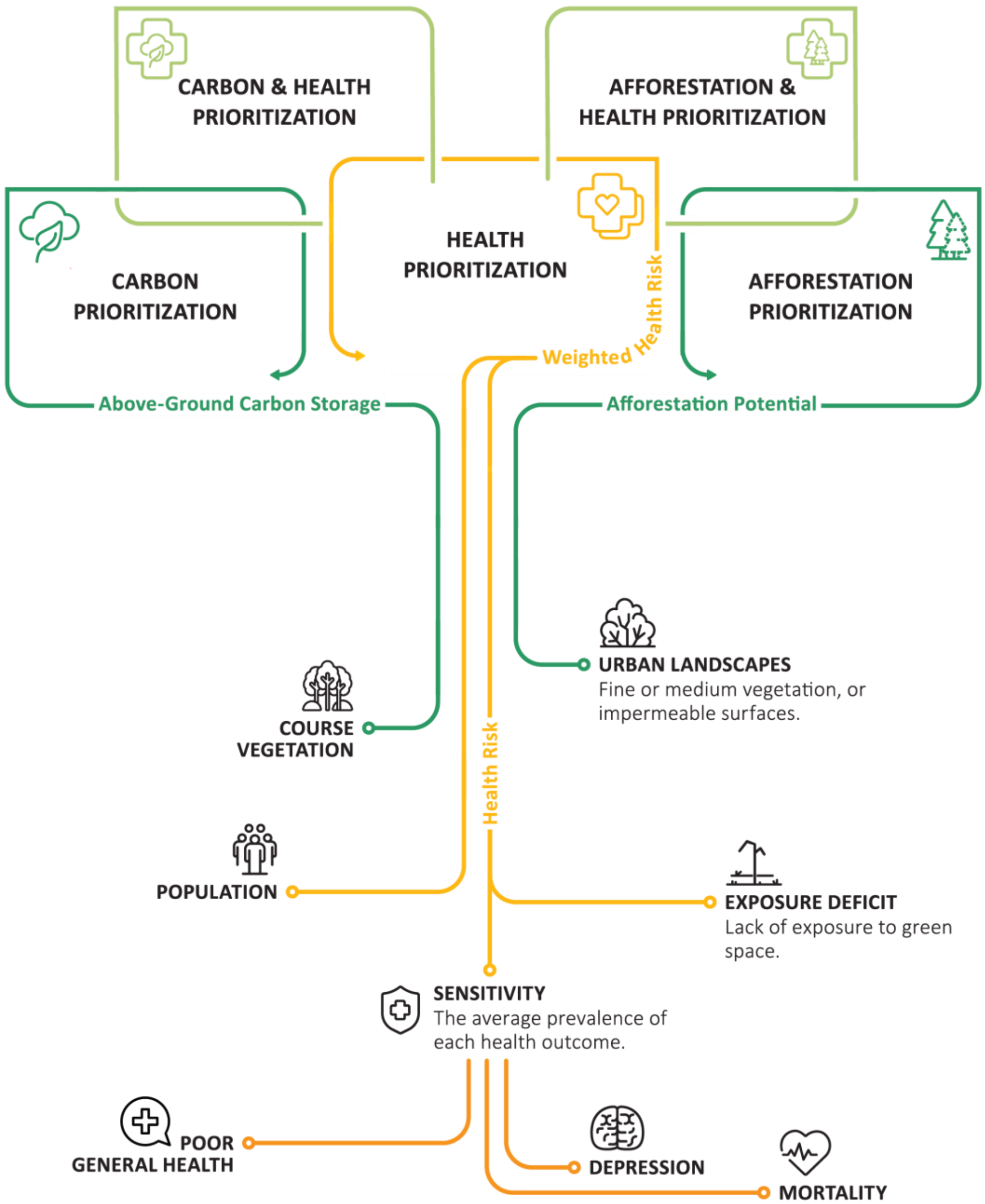

Figure 2. Overview of methodology. The priority of census tracts for storing carbon is a function of percent area of coarse vegetation in each census tract. The priority of census tracts based on the potential to augment carbon sequestration through afforestation is a function of the percent area in each census tract where trees could be added. The priority of census tracts for improving human health through exposure to green space is a function of population size, sensitivity, and exposure deficit. The priority of census tracts for achieving multiple objectives is the average of two single-objective priorities. Figure credit: SJ Bowden.

All analyses were conducted at the scale of census tracts due to the availability of U.S. Census-derived socioeconomic data and region-wide health data. We conducted analyses using health and demographic data from the 2010 U.S. Census, the most recent data available. Statistical analyses were conducted using R (version 4.2.1). Spatial analyses and mapping were conducted using ArcGIS Pro (version 3.0.0).

Existing Carbon Storage and the Potential to Augment Carbon Sequestration

Our first step was to prioritize census tracts based on the relative magnitude of the carbon benefit that deployment of afforestation or avoided forest conversion could provide within the census tract. Because the carbon benefit provided by the addition of small, young trees through afforestation is smaller than the carbon benefit provided by protecting existing trees through avoided forest conversion (Ravindranath et al., 2008), we prioritized census tracts for (1) existing carbon storage and (2) the potential to augment carbon sequestration through afforestation.

First, we used 1-meter resolution land-cover data developed from land-use and remote sensing data collected between 2016 and 2020 (*Stormwater Heatmap*, 2023) to calculate the percent area of coarse vegetation in each census tract, which was used as a proxy for existing carbon storage. Census tracts with higher percentages of coarse vegetation and, thereby greater carbon storage, were ranked higher in this prioritization scheme.

Then, using the land-cover dataset described above (*Stormwater Heatmap*, 2023), we estimated the area in each census tract where trees could be added by calculating the percent area in each census tract with fine vegetation (e.g., grasses), medium vegetation (e.g., shrubs and bushes), or impervious surfaces except roofs (e.g., roads, sidewalks, parking lots). This metric was used as a proxy for the potential for afforestation to augment carbon sequestration. We did not consider cells categorized as roofs in our estimation of the area where trees could be added because afforestation is unlikely in these places. We also did not include cells categorized as bare soil (i.e., dirt) in our estimates of areas where trees could be added because the amount of bare soil was unknown in many census tracts (*Stormwater Heatmap*, 2023). Ultimately, census tracts with higher percentages of fine vegetation, medium vegetation, and impervious surfaces were ranked higher in our prioritization scheme, as those census tracts may provide relatively more opportunities for carbon sequestration to be augmented through afforestation.

Health Risk

Next, we developed a metric of health risk that focused on health metrics that are known to be positively impacted by green space. Using principles of conventional risk assessments (Samhouri & Levin, 2011) and health impact assessments (National Research Council, 2011), we estimated the risk to health in a census tract as the combination of the lack of exposure to green space and the sensitivity to adverse health outcomes that can be reduced through exposure to green space, as described below.

Health Outcomes

We conducted a literature review to identify health outcomes that were suitable for inclusion in our calculation of the sensitivity of the population in each census tract to adverse health outcomes. First, we identified four literature reviews published in the last ten years that systematically evaluated the impact of green space on various health outcomes: James et al. (2015), Fong et al. (2018), Frumkin et al. (2017), and Wolf (2020). Then, we evaluated each of the 24 health outcomes discussed in these literature reviews according to three criteria: (1) data on the prevalence of the health outcome is publicly available at the census tract scale for the Puget Sound region, (2) the adverse health outcome is improved with increased exposure to green space, and (3) the strength of scientific evidence associating the health outcome with exposure to green space is high, such that evidence is “consistent, plausible, and precisely quantified and there is low probability of bias” (James et al., 2015, p. 133).

To assess data availability, we searched the Washington Tracking Network (Washington State Department of Health, n.d.), the Center for Disease Control and Prevention (CDC) PLACES database (Centers for Disease Control and Prevention, 2022), and Behavioral Risk Factor Surveillance System (BRFSS) database (*Behavioral Risk Factor Surveillance System*, 2023) for census tract level data on the prevalence of each of the 24 candidate health outcomes. For each of the health outcomes with census tract level data available, we then evaluated the directionality of the relationship and the strength of the evidence by synthesizing findings from the four literature reviews. We ultimately identified three health outcomes that met all criteria: general health, mortality from all causes, and depression (Table 1).

Adverse Health Outcome	Data	Direction and Strength
General Health and Well-Being		
General Health, Adults[3]	Yes	Consistent, positive association
General Health, Children[3]	No	
General Health, Cancer Survivor[3]	No	
Mortality, All Causes[1,2,3,4]	Yes	Consistent, negative association
Physical Health		
Asthma and Allergies[2,3,4]	Yes	Inconsistent results
Birth Outcomes[1,2,3,4]	No	
Blood Pressure[3]	Yes	Not well-studied; inconsistent results
Cancer[4]	Yes	Not well-studied; inconsistent results
Cardiovascular Disease[1,2,3,4]	Yes	Inconsistent results
Development, Cognitive/Motor[3]	No	
Diabetes[3,4]	Yes	Not well-studied
Eyesight[3]	No	
Immune System Function[3]	No	
Obesity[1,2,3,4]	Yes	Inconsistent results
Pain, Acute and Chronic[3]	No	

Recovery, Postoperative[3]	No	
Mental Health		
Aggression and Violence[3,4]	No	
Anxiety[3]	No	
Depression[3,4]	Yes	Consistent, negative association
Psychological Well-being[1,3,4]	Yes	Inconsistent results
Stress[3]	No	
Behavioral Health		
ADHD[3]	No	
Pro-Social Behavior[3]	No	
Sleep[3]	No	

Table 1. Summary of findings from literature review aimed at identifying health outcomes for inclusion in calculation of sensitivity to adverse health outcomes. Three adverse health outcomes (1) were consistently shown to be improved by increased exposure to green space and (2) had consistent, plausible, and precisely quantified results with a low probability of bias: general health (in adults), mortality from all causes, and depression. Health outcomes studied in James et al. (2015), Fong et al. (2018), Frumkin et al. (2017), and Wolf (2020) are superscripted with a 1, 2, 3, and 4, respectively. ADHD is attention-deficit/hyperactivity disorder.

Sensitivity

To estimate the sensitivity of populations in each census tract to adverse health outcomes that can be improved through exposure to green space, we first obtained census tract-level age-adjusted data on the prevalence of each health outcome in each census tract. Data on the prevalence of all-cause mortality were obtained from the Washington State Department of Health's Washington Tracking Network as age-adjusted rates of adults (age ≥ 18) per 100,000 people between 2016 and 2020 (Washington State Department of Health, n.d.). Data on the prevalence of depression and fair or poor self-reported general health were obtained from the CDC's PLACES database as age-adjusted percentages of adults (age ≥ 18) in 2020 diagnosed with depression and self-reporting fair or poor general health, respectively (Centers for Disease Control and Prevention, 2022).

Then, we divided the prevalence of each health outcome in each census tract by the highest reported prevalence in the region, thereby rescaling the prevalence of each health outcome so that all values fell between zero and one. To create a proxy for the sensitivity of the population in each census tract to adverse health outcomes that could be reduced through exposure to green space, we calculated the arithmetic mean of the rescaled prevalence of each health outcome in each census tract. We used this metric as a proxy for the sensitivity of the population in each census tract to adverse health outcomes that have been shown to be improved through exposure to green space.

Exposure Deficit

Using 1-meter resolution land cover data (*Stormwater Heatmap*, 2023), we estimated the percent area of each census tract that lacked green space and used this metric as a proxy for the exposure deficit (i.e., lack of exposure to green space) of the population in each census tract. To do so, we divided the number of the 1-meter cells categorized as coarse vegetation, medium vegetation, or fine vegetation, respectively, in each census tract by the number of 1-meter cells in the tract, and then subtracted these decimal values from one.

Weighted Community Health Risk

We then defined weighted community health risk *R* as the Euclidean distance of the population *P* in each census tract from the origin in a theoretical three-dimensional space defined by (1) the sensitivity *S* of the population to adverse health outcomes that can be improved by green space, (2) the lack of exposure *E* to green space, and (3) the size of the population *N* in the census tract (Equation 1).

$$R_p = \sqrt{S^2 + E^2 + N^2} \tag{1}$$

We rescaled exposure, sensitivity, and population size so that they ranged from zero to one by dividing each value by the maximum respective values in the sample. With this approach, census tracts with greater sensitivity to adverse health outcomes, less green space, and more people were considered higher risk.

Multiple Objective Prioritizations

To determine which census tracts should receive the highest priority for jointly achieving carbon and health benefits, we rescaled both the carbon prioritization scheme and the health prioritization scheme by dividing each value by the maximum so each ranged from zero to one. Then, for each census tract, we simply averaged the ranks. Thus, census tracts with higher average ranks are considered higher priority than those with lower average ranks. This approach tends to prioritize areas where existing trees and forests store relatively large amounts of carbon and may substantially support human health by reducing adverse health outcomes. As such, this prioritization scheme identifies census tracts where avoided forest conversion may be a particularly appropriate management action, as it could safeguard existing carbon and health co-benefits in the census tract.

We repeated this process for the afforestation and health prioritization by using the afforestation prioritization scheme in our calculation in place of the carbon prioritization scheme. By prioritizing census tracts with relatively high afforestation priorities as well as relatively high health priorities, our afforestation and health prioritization scheme identifies census tracts where there are relatively more opportunities to augment carbon sequestration and improve human health through afforestation. As such, this prioritization scheme identifies census tracts where adding green space through afforestation may be a particularly appropriate management action.

Statistical Analyses

The approach described above yielded five distinct prioritization schemes: carbon, afforestation, health, carbon and health, and afforestation and health. To visualize the spatial distribution of relatively high, medium, and low priorities in the five prioritization schemes, we mapped each prioritization scheme, using a multicolor gradient to visualize the relative priority of each census tract.

We also examined the relationship between each of the prioritization schemes and four metrics of interest: percent urban, percent impervious surface, average population density, and percent People of Color. Percent urban was calculated as the area in each census tract that was within an urban area (U.S. Geological Survey, n.d.) divided by the total census tract area (U.S. Geological Survey, n.d.). Similarly, percent impervious surface was calculated as the area in each census tract covered by impervious surfaces, including roofs, roads, sidewalks, parking lots, etc. (*Stormwater Heatmap*, 2023) divided by the total census tract area (U.S. Geological Survey, n.d.). Average population density was calculated as the population in the census tract (United States Census Bureau, n.d.) divided by the total census tract area (U.S. Geological Survey, n.d.). Percent People of Color was calculated as the number of residents in each census tract identifying as non-White (i.e., Black, American Indian and Alaska Native (AIAN), Asian, Native Hawaiian and other Pacific islander (NHOPI), other (of one race only), two or more races, or Hispanic; United States Census Bureau, n.d.) divided by the total number of people living in the census tract (United States Census Bureau, n.d.).

To visualize the relationship between each prioritization scheme and each metric of interest, we plotted the metric of interest against the priority assigned to each census tract under the given prioritization scheme. We also computed Spearman's rank correlations to assess the relationship between the rank assigned to census tracts in the prioritization scheme and the four metrics of interest. To more thoroughly examine possible associations between each of the five prioritization schemes and specific racial groups, we computed Spearman's rank correlations between each prioritization scheme and the percent of people in each census tract identifying as Black, American Indian and Alaska Native (AIAN), Asian, Native Hawaiian and other Pacific islander (NHOPI), other (of one race only), two or more races, or Hispanic.

We used box plots to examine how the variance in the percent urban, percent impervious surface, population density, and percent People of Color varied between census tracts in the top ten percent of each of the five prioritization schemes.

Results

Carbon Prioritization

Our analysis revealed that census tracts in and around metropolitan areas are relatively low priority for storing carbon and census tracts in less developed areas are generally higher priority (Figure 3).

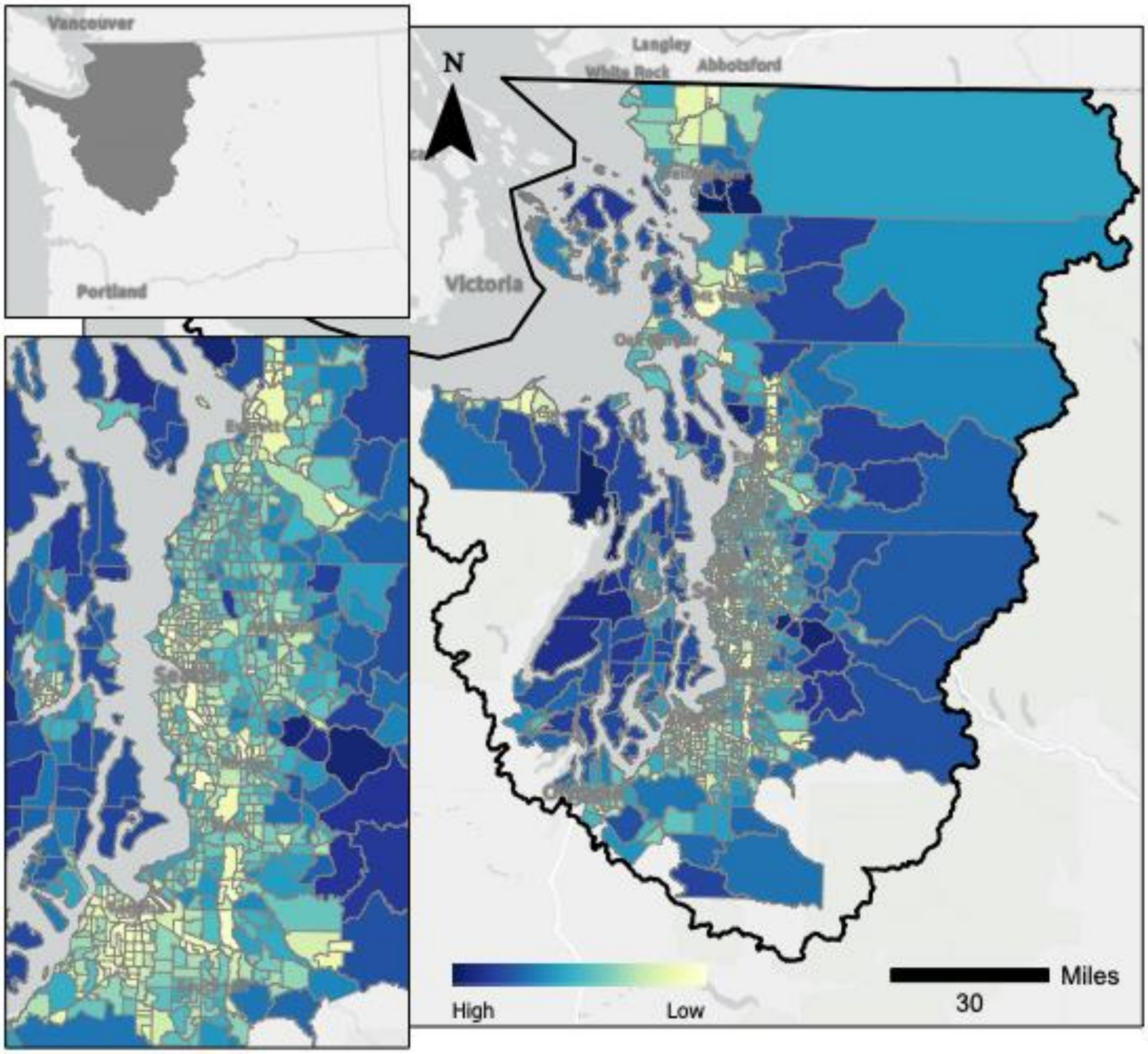

Figure 3. The spatial distribution of the carbon prioritization, defined as the priority of census tracts for maintaining existing carbon storage. Census tracts with higher percentages of coarse vegetation and, thereby greater carbon storage, ranked higher in this prioritization. Study area is outlined in black. Grey areas within this boundary were omitted from the analysis due to insufficient or unreliable data. Top inset map shows the location of the study area within the State of Washington, USA. Bottom inset map magnifies smaller census tracts in and around metropolitan centers (e.g., Everett, Seattle, Tacoma).

Ranks of census tracts based on carbon storage are inversely correlated with the percent cover of impervious surfaces in census tracts ($\rho = -0.83$; $p < 0.001$; Figure 4 top left), the population density of census tracts ($\rho = -0.60$; $p < 0.001$; Figure 4 top right), and the percent

People of Color in census tracts (ρ = -0.42; $p < 0.001$; Figure 4 bottom left), as well as the percent of people in the census tract that identify as Black (ρ = -0.47; $p < 0.001$), American Indian or Alaskan Native (ρ = -0.23; $p < 0.001$), Asian (ρ = -0.22; $p < 0.001$), Native Hawaiian or Pacific Islander (ρ = -0.29; $p < 0.001$), other of one race (ρ = -0.45; $p < 0.001$), two or more races (ρ = -0.37; $p < 0.001$), or Hispanic (ρ = -0.49; $p < 0.001$).

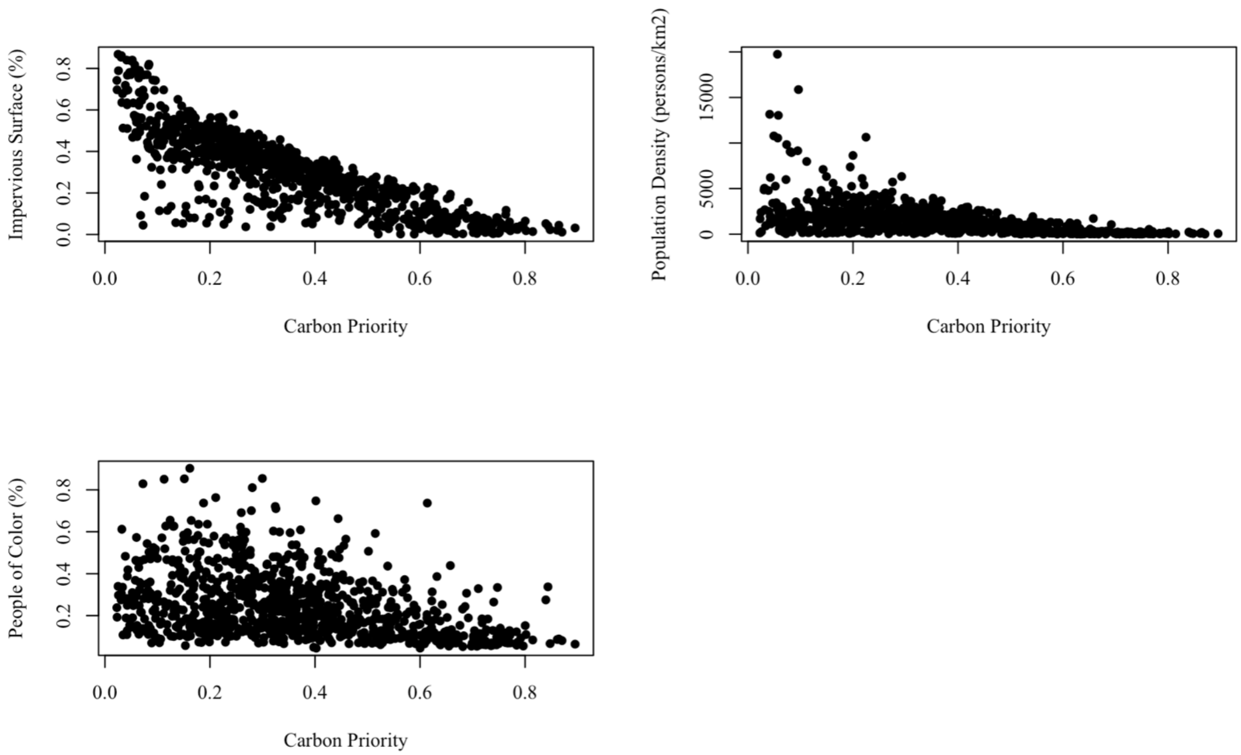

Figure 4. Plots of the 928 census tracts in the Puget Sound region using the carbon priority of a census tract versus (top left) percent cover of impervious surface, (top right) population density, and (bottom left) percent People of Color.

Afforestation Prioritization

Our analysis also revealed that census tracts in and around metropolitan areas are relatively high priority for augmenting carbon sequestration through afforestation and census tracts in less developed areas are generally lower priority (Figure 5).

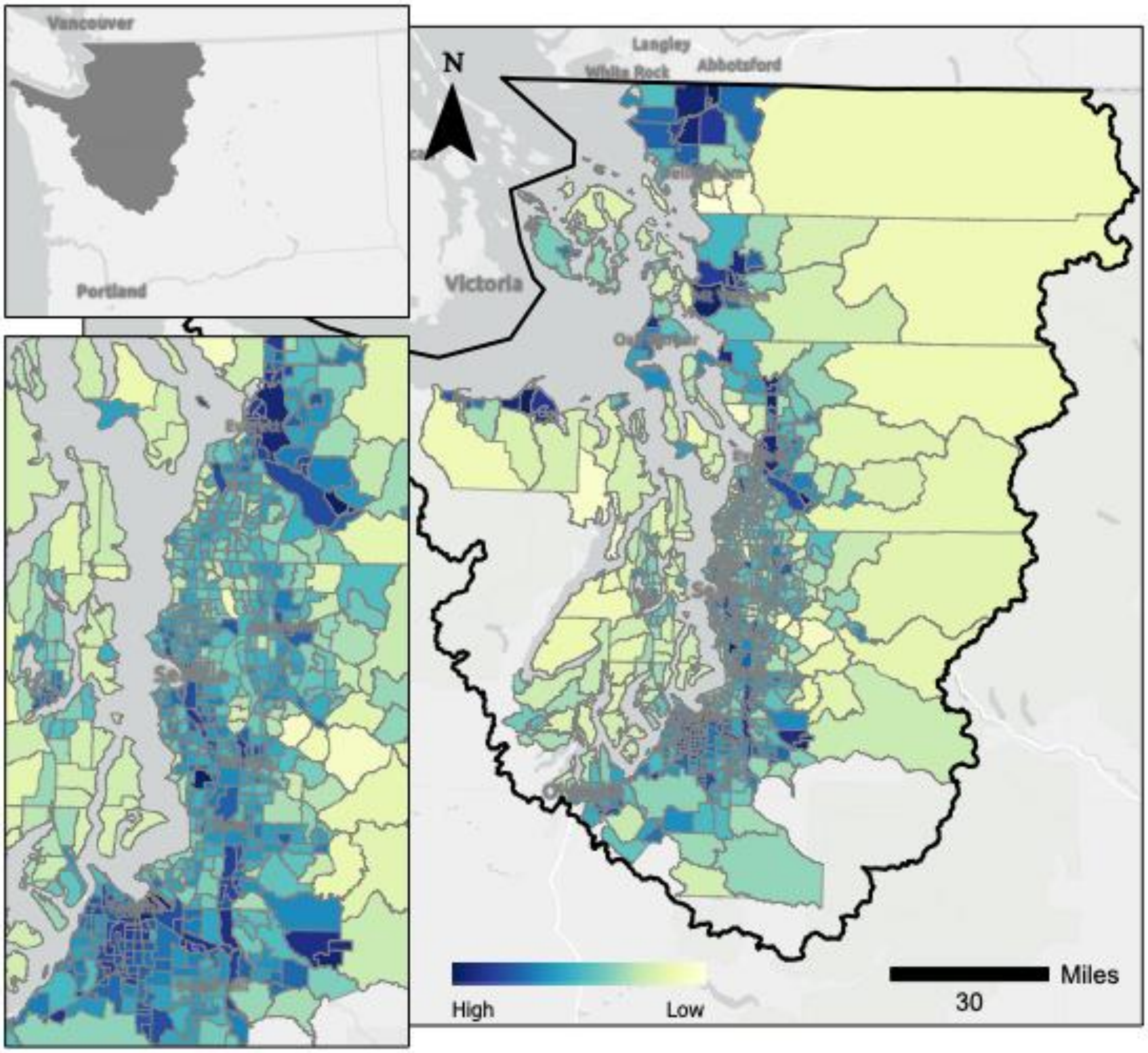

Figure 5. The spatial distribution of the afforestation prioritization, defined as the priority of census tracts based on the potential to increase carbon sequestration through afforestation. Census tracts with higher percent area of fine and medium vegetation and impervious surfaces ranked higher in this prioritization. Study area is outlined in black. Grey areas within this boundary were omitted from the analysis due to insufficient or unreliable data. Top inset map shows the location of the study area within the State of Washington, USA. Bottom inset map magnifies smaller census tracts in and around metropolitan centers (e.g., Everett, Seattle, Tacoma).

Ranks of census tracts based on the potential to increase carbon sequestration are positively correlated with percent cover of impervious surfaces in census tracts ($\rho = 0.62$; $p < 0.001$; Figure 6 top left), population density of census tracts ($\rho = 0.34$; $p < 0.001$; Figure 6 top right), and percent People of Color in census tracts (ρ = 0.35; p < 0.001; Figure 6 bottom left), as well as the percent of people in census tracts that identify as Black (ρ = 0.40; p < 0.001), American Indian or Alaskan Native (ρ = 0.33; p < 0.001), Asian (ρ = 0.09; p < 0.001), Native Hawaiian or Pacific Islander (ρ = 0.35; p < 0.001), other of one race (ρ = 0.50; p < 0.001), two or more races (ρ = 0.36; p < 0.001), or Hispanic (ρ = 0.54; p < 0.001).

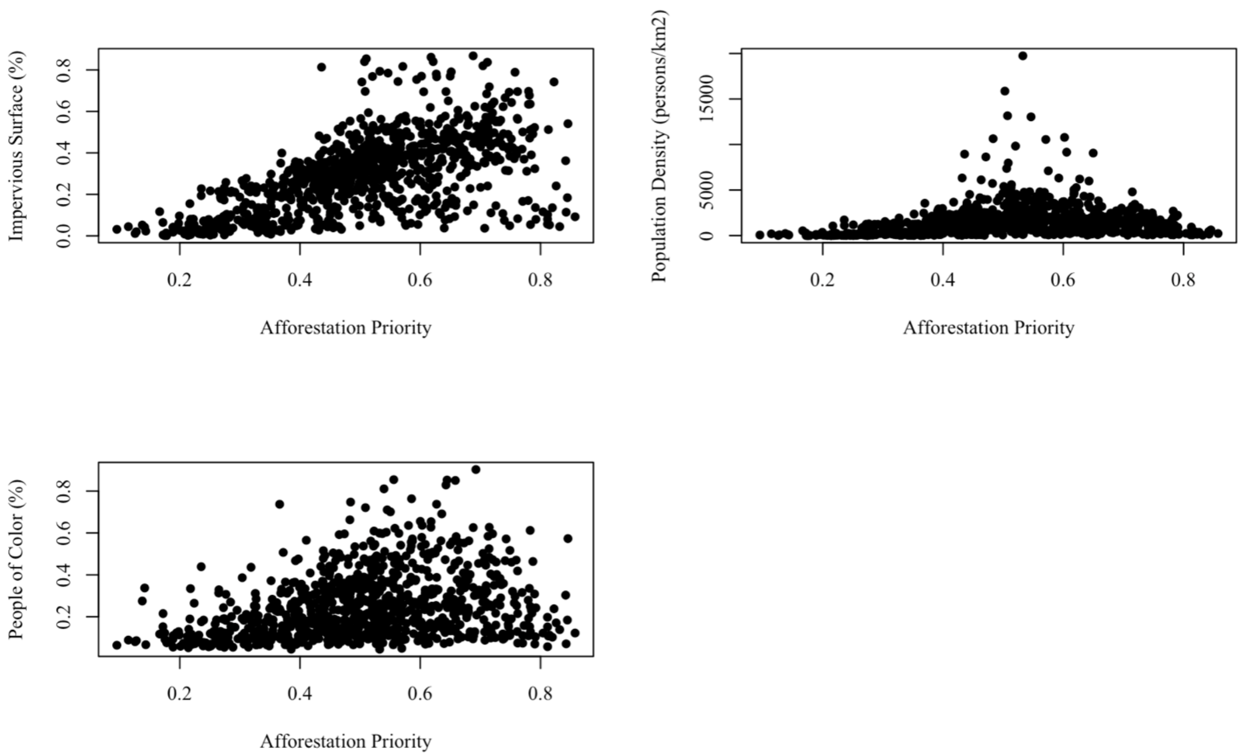

Figure 6. Plots of the 928 census tracts in the Puget Sound region using the afforestation priority of a census tract versus (top left) percent cover of impervious surface, (top right) population density, and (bottom left) percent People of Color.

Health Prioritization

Similarly, our analysis revealed that census tracts in and around metropolitan areas are relatively high priority for reducing adverse health outcomes through exposure to green space and census tracts in less developed areas are generally lower priority (Figure 7).

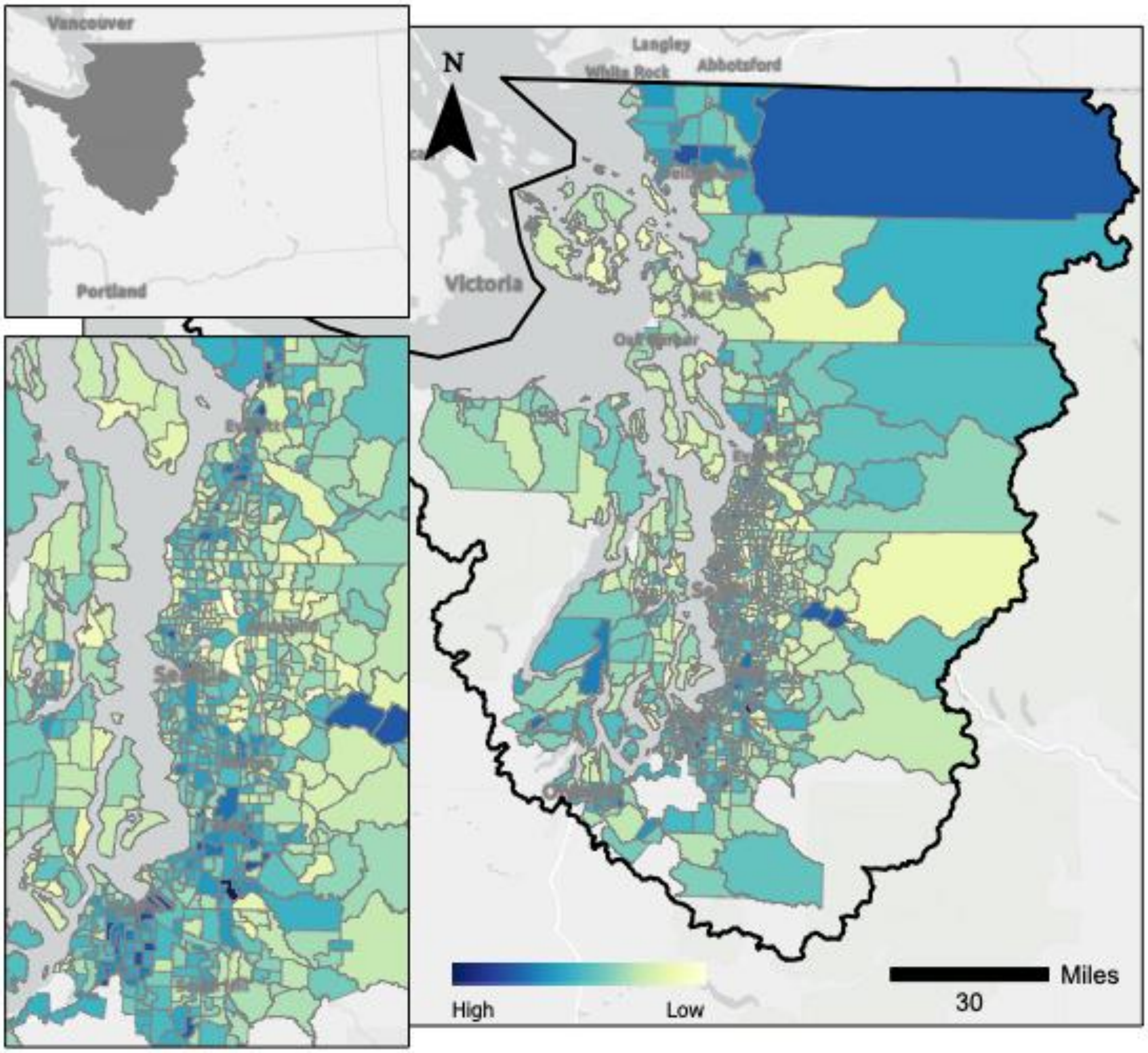

Figure 7. The spatial distribution of the health prioritization, defined as the priority of census tracts based on the potential to reduce adverse health outcomes through exposure to green space. Census tracts with higher sensitivity, greater exposure deficit, and larger population size ranked higher in this prioritization. Study area is outlined in black. Grey areas within this boundary were omitted from the analysis due to insufficient or unreliable data. Top inset map shows the location of the study area within the State of Washington, USA. Bottom inset map magnifies smaller census tracts in and around metropolitan centers (e.g., Everett, Seattle, Tacoma).

Ranks of census tracts based on the potential to reduce adverse health outcomes through exposure to green space are positively correlated with percent cover of impervious surfaces in census tract ($\rho = 0.52$; $p < 0.001$; Figure 8 top left), population density of census tracts ($\rho = 0.37$;

p < 0.001; Figure 8 top right), and percent People of Color in census tracts (ρ = 0.43; p < 0.001; Figure 8 bottom left), as well as the percent of people in census tracts that identify as Black (ρ = 0.46; p < 0.001), American Indian or Alaskan Native (ρ = 0.46; p < 0.001), Asian (ρ = 0.12; p < 0.001), Native Hawaiian or Pacific Islander (ρ = 0.46; p < 0.001), other of one race (ρ = 0.51; p < 0.001), two or more races (ρ = 0.44; p < 0.001), or Hispanic (ρ = 0.56; p < 0.001).

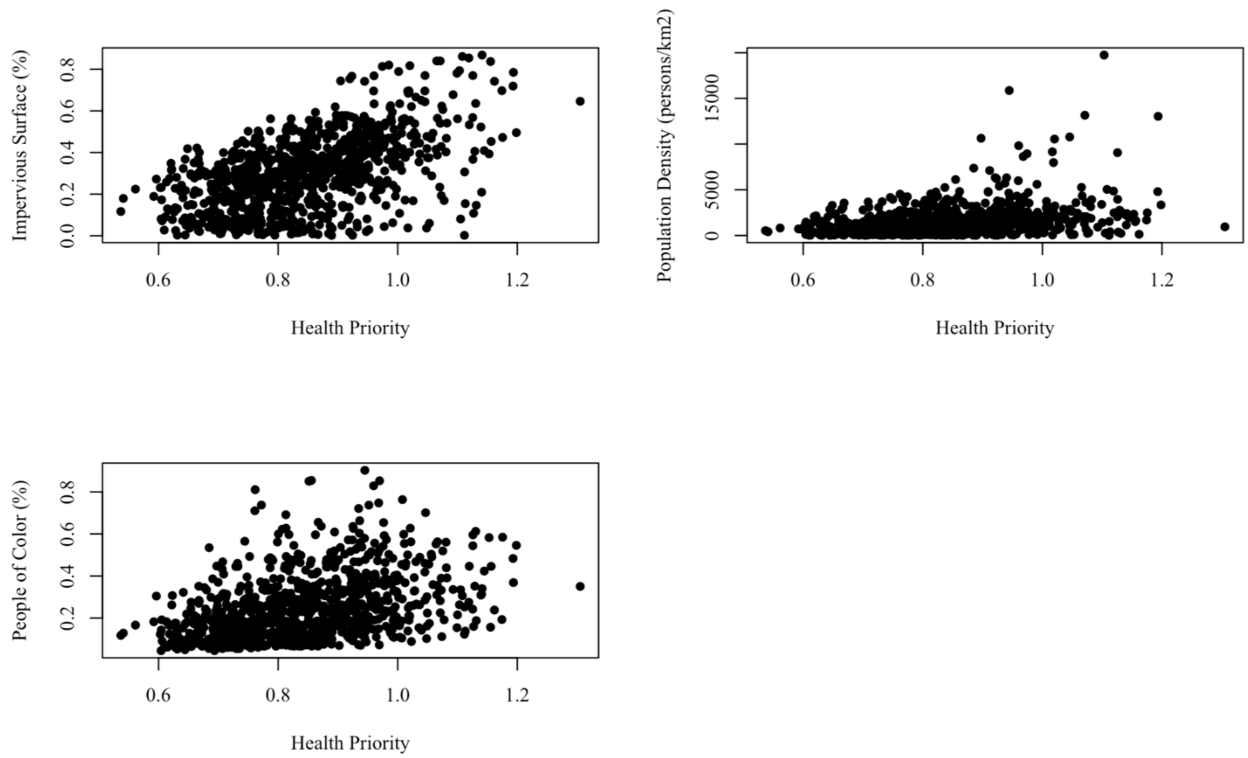

Figure 8. Plots of the 928 census tracts in the Puget Sound region using the health priority of a census tract versus (top left) percent cover of impervious surface, (top right) population density, and (bottom left) percent People of Color.

Carbon and Health Prioritization

Our analysis revealed that census tracts in and around metropolitan areas are relatively low priority for storing carbon and supporting health and census tracts in less developed areas are generally higher priority (Figure 9).

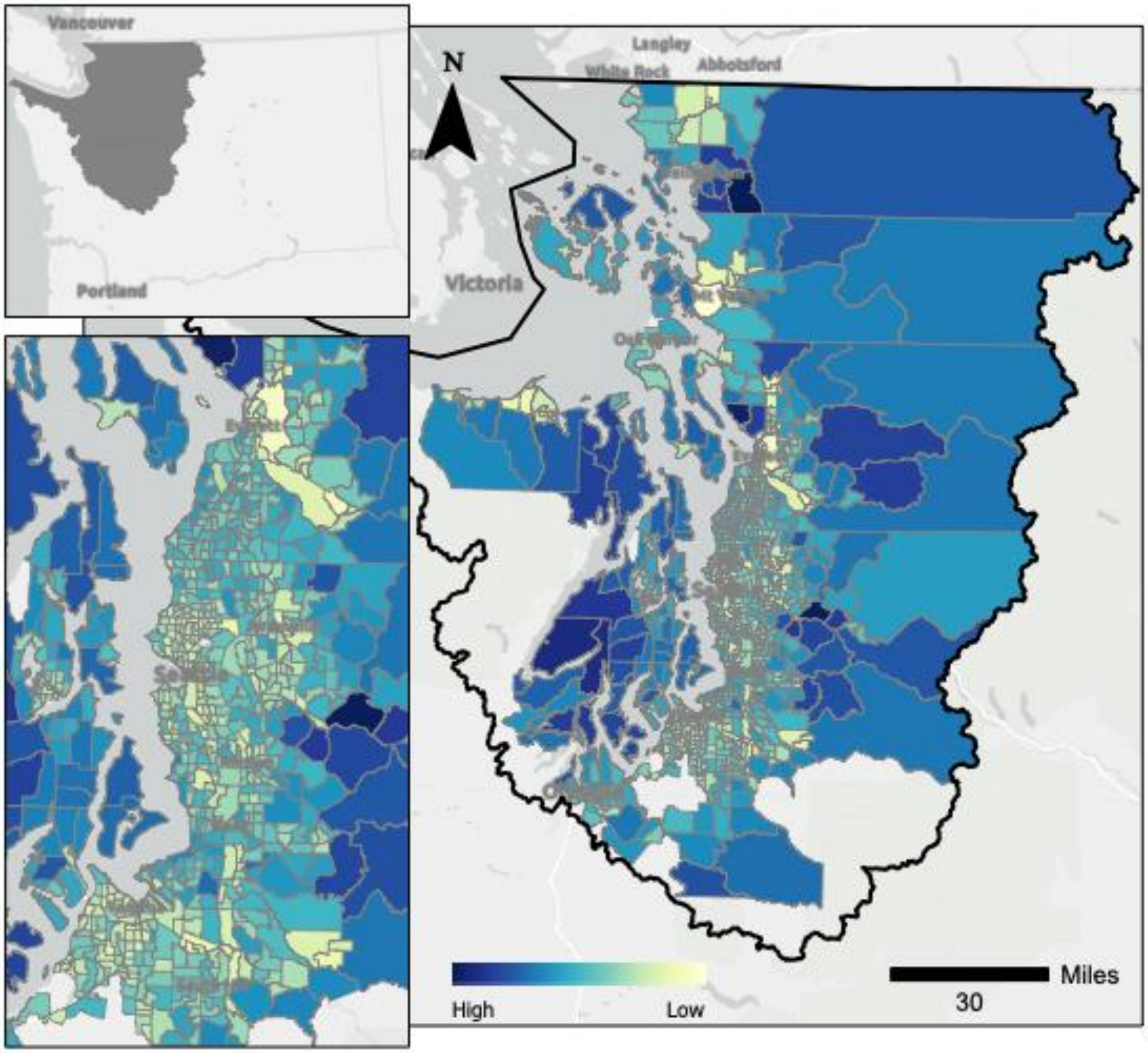

Figure 9. The spatial distribution of the carbon and health prioritization, defined as the priority of census tracts based on existing carbon storage and the potential to reduce adverse health outcomes. Census tracts that ranked high in both associated single-objective prioritizations ranked higher in this prioritization. Study area is outlined in black. Grey areas within this boundary were omitted from the analysis due to insufficient or unreliable data. Top inset map shows the location of the study area within the State of Washington, USA. Bottom inset map magnifies smaller census tracts in and around metropolitan centers (e.g., Everett, Seattle, Tacoma).

Ranks of census tracts based on carbon storage and the potential to reduce adverse health outcomes through exposure to green space are inversely correlated with percent cover of impervious surfaces in census tracts (ρ = -0.71; $p < 0.001$; Figure 10 top left), population density of census tracts (ρ = -0.52; $p < 0.001$; Figure 10 top right), and percent People of Color in census tracts (ρ = -0.28; $p < 0.001$; Figure 10 bottom left), as well as percent of people in census tracts that identify as Black (ρ = -0.32; $p < 0.001$), Asian (ρ = -.20; $p < 0.001$), Native Hawaiian or Pacific Islander (ρ = -0.10; $p = 0.002$), other of one race (ρ = -0.27; $p < 0.001$), two or more races (ρ = -0.22; $p < 0.001$), or Hispanic (ρ = -0.29; $p < 0.001$). There was no correlation between ranks of census tracts based on carbon storage and the potential to reduce adverse health outcomes and percent American Indian or Alaskan Native (ρ = -0.03; $p = 0.377$).

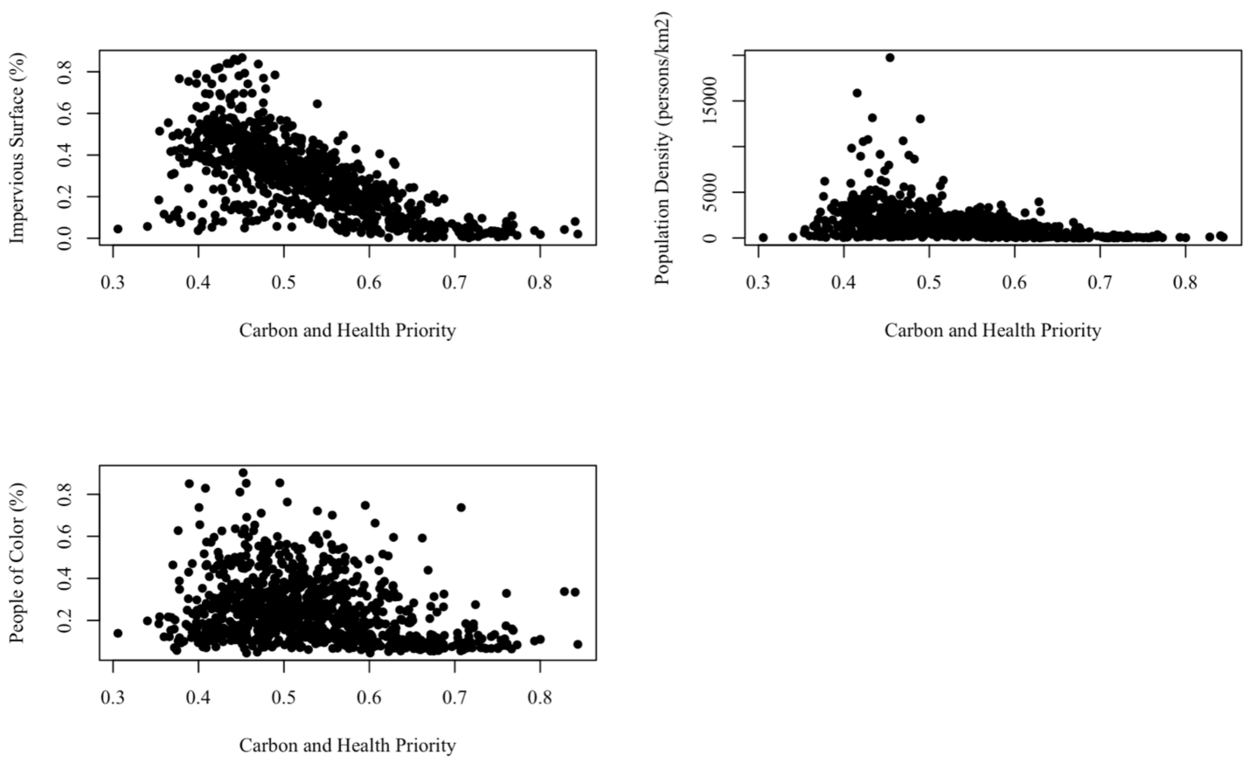

Figure 10. Plots of the 928 census tracts in the Puget Sound region using the carbon and health priority of a census tract versus (top left) percent cover of impervious surface, (top right) population density, and (bottom left) percent People of Color.

Afforestation and Health Prioritization

Our analysis revealed that census tracts in and around metropolitan areas are generally higher priority for increasing carbon sequestration through afforestation and supporting health through exposure to green space. Conversely, the priority of census tracts for achieving these objectives is generally lower in less developed areas (Figure 11).

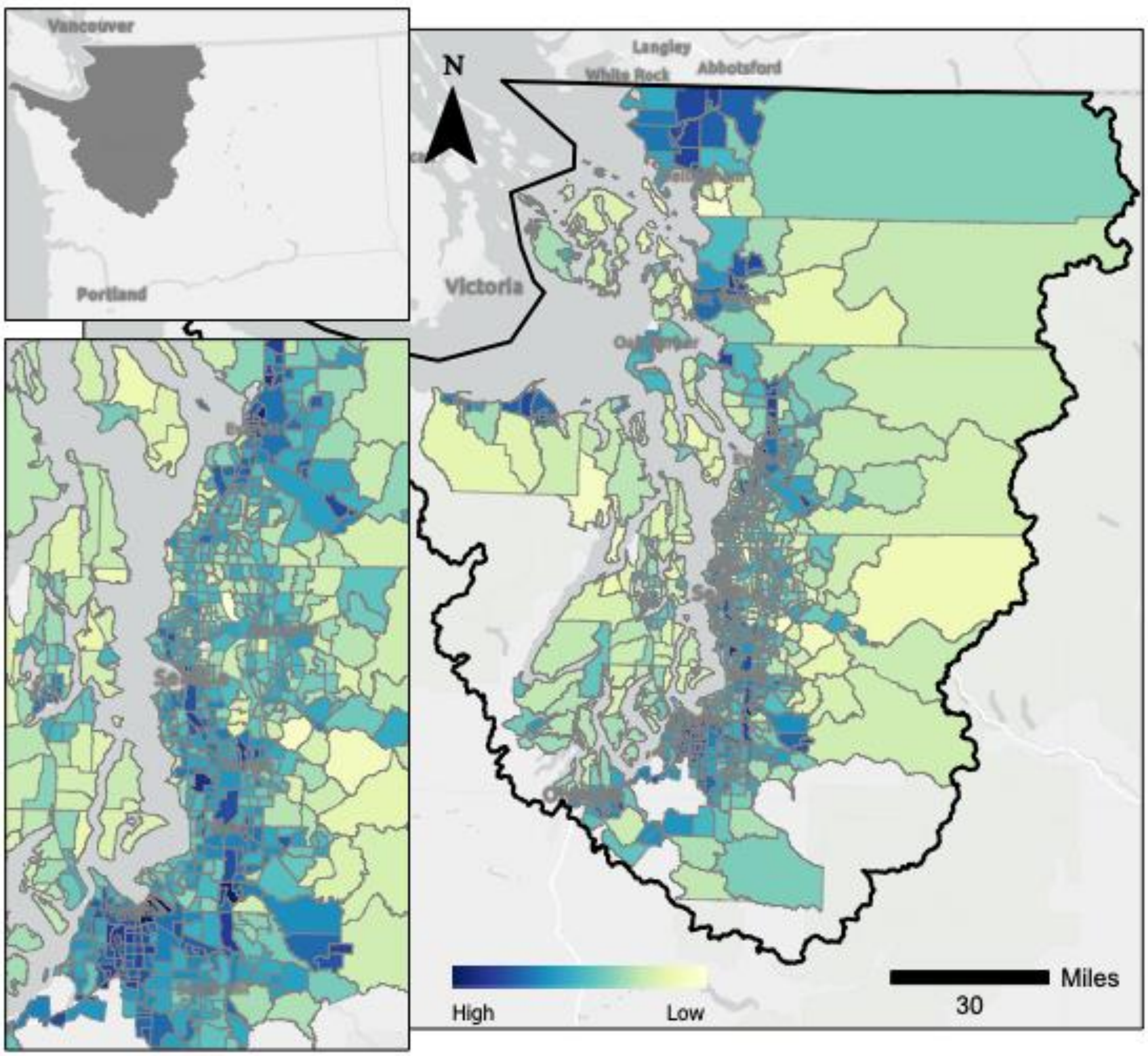

Figure 11. The spatial distribution of the afforestation and health prioritization, defined as the priority of census tracts based on the potential to both increase carbon sequestration through

afforestation and reduce adverse health outcomes through exposure to green space. Census tracts that ranked high in both associated single-objective prioritizations ranked higher in this prioritization. Study area is outlined in black. Grey areas within this boundary were omitted from the analysis due to insufficient or unreliable data. Top inset map shows the location of the study area within the State of Washington, USA. Bottom inset map magnifies smaller census tracts in and around metropolitan centers (e.g., Everett, Seattle, Tacoma).

Ranks of census tracts based on the potential to increase carbon sequestration and reduce adverse health outcomes through green space are positively correlated with percent cover of impervious surfaces in census tracts ($\rho = 0.66$; $p < 0.001$; Figure 12 top left), population density of census tracts ($\rho = 0.40$; $p < 0.001$; Figure 12 top right), and percent People of Color in census tracts ($\rho = 0.42$; $p < 0.001$; Figure 12 bottom left), as well as percent of people in census tracts that identify as Black ($\rho = 0.47$; $p < 0.001$), American Indian or Alaskan Native ($\rho = 0.41$; $p < 0.001$), Asian ($\rho = 0.11$; $p < 0.001$), Native Hawaiian or Pacific Islander ($\rho = 0.43$; $p < 0.001$), other of one race ($\rho = 0.57$; $p < 0.001$), two or more races ($\rho = 0.43$; $p < 0.001$), or Hispanic ($\rho = 0.62$; $p < 0.001$).

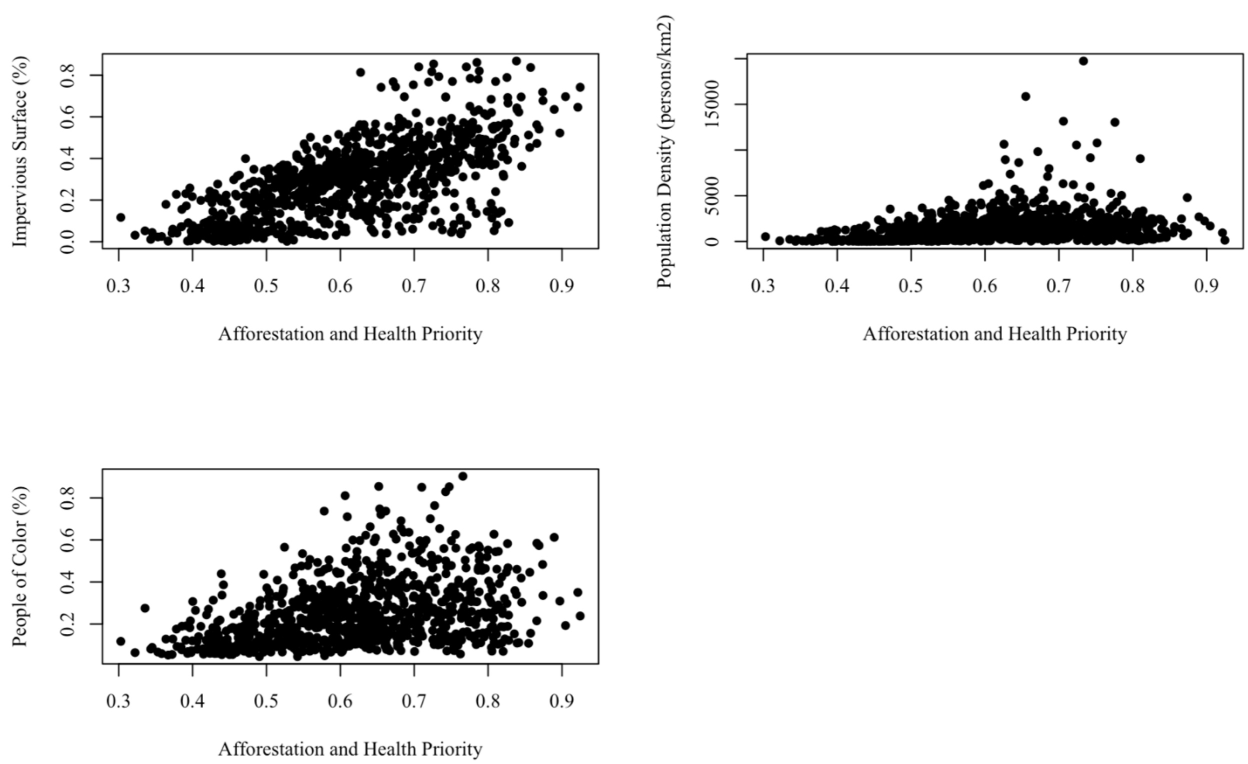

Figure 12. Plots of the 928 census tracts in the Puget Sound region using the afforestation and health priority of a census tract versus (top left) percent cover of impervious surface, (top right) population density, and (bottom left) percent People of Color.

Outcomes of Prioritizations

For all metrics of interest (i.e., percent of a census tract considered urban, percent cover of impervious surfaces, population density, or percent People of Color), the census tracts in the top 10% of the carbon prioritization scheme tended to be similar to the census tracts in the top 10% of the carbon and health prioritization scheme, but dissimilar from the census tracts in the top 10% of the afforestation, health, and afforestation and health prioritization schemes.

Impervious Surface

Census tracts ranked high in the carbon prioritization scheme and the carbon and health prioritization scheme generally had a lower percent cover of impervious surface than census tracts ranked high in the afforestation, health, and afforestation and health prioritization schemes (Figure 13). At least 75% of the census tracts in the top 10% of the carbon prioritization scheme and the carbon and health prioritization scheme consisted of 10% or less impervious surface. By contrast, half of the census tracts in the top 10% of the afforestation, health, and afforestation and health prioritization schemes had impervious surfaces covering 45% or more of the census tract. However, the percentage of impervious surface cover for census tracts ranked high in these three prioritization schemes varied greatly, such that some census tracts in the first quartiles had less than 10% impervious surface.

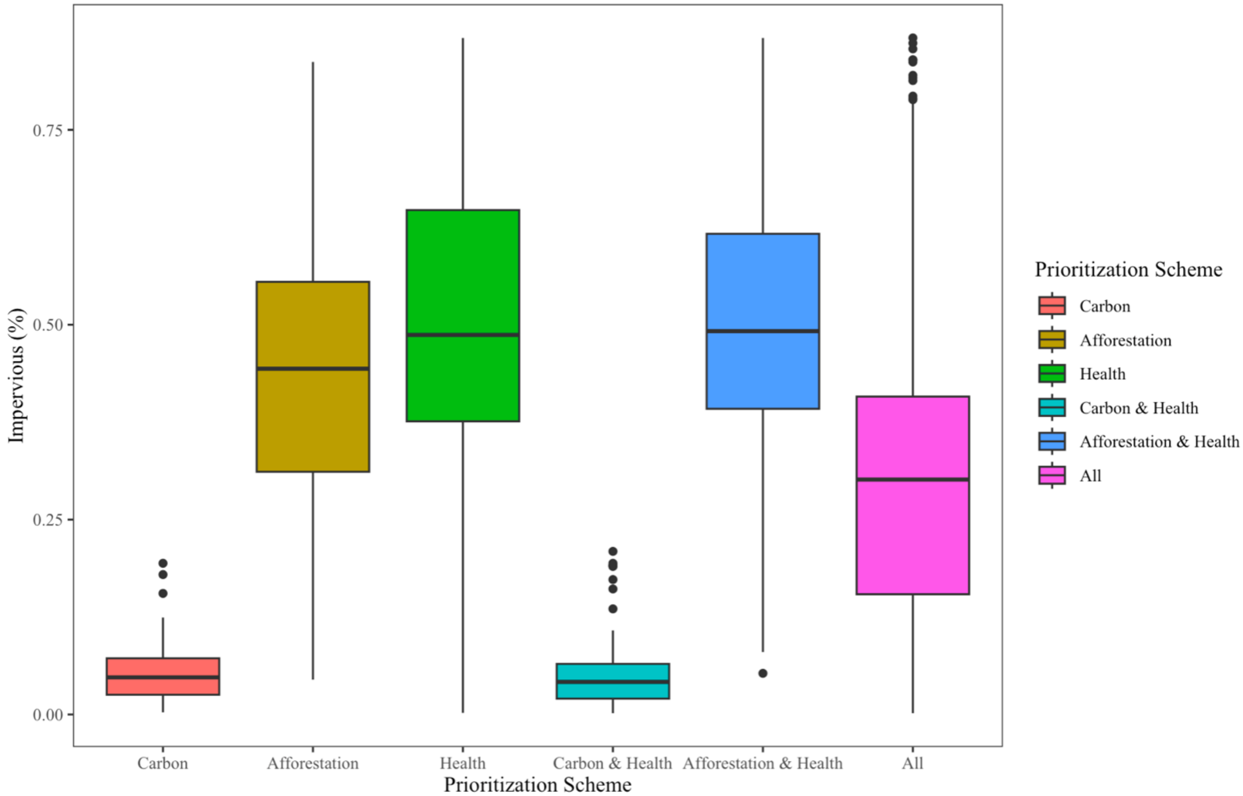

Figure 13. Box plots of percent impervious for the top 10% of census tracts in each of the five prioritization schemes and in all 928 census tracts in the study area.

Population Density

Census tracts ranked high in the carbon prioritization scheme and the carbon and health prioritization scheme generally had lower average population densities than census tracts ranked high in the afforestation, health, and afforestation and health prioritization schemes (Figure 14). Most of the census tracts in the top 10% of the carbon prioritization and the carbon and health prioritization scheme had average population densities of 250 people per square kilometer or less. By contrast, 75% of the census tracts in the top 10% of the afforestation, health, and afforestation and health prioritization schemes had average population densities above this threshold. Census tracts in the top 10% of the health prioritization scheme had the highest average population densities, followed by census tracts in the top 10% of the afforestation and health prioritization scheme and then census tracts in the top 10% of the afforestation prioritization scheme.

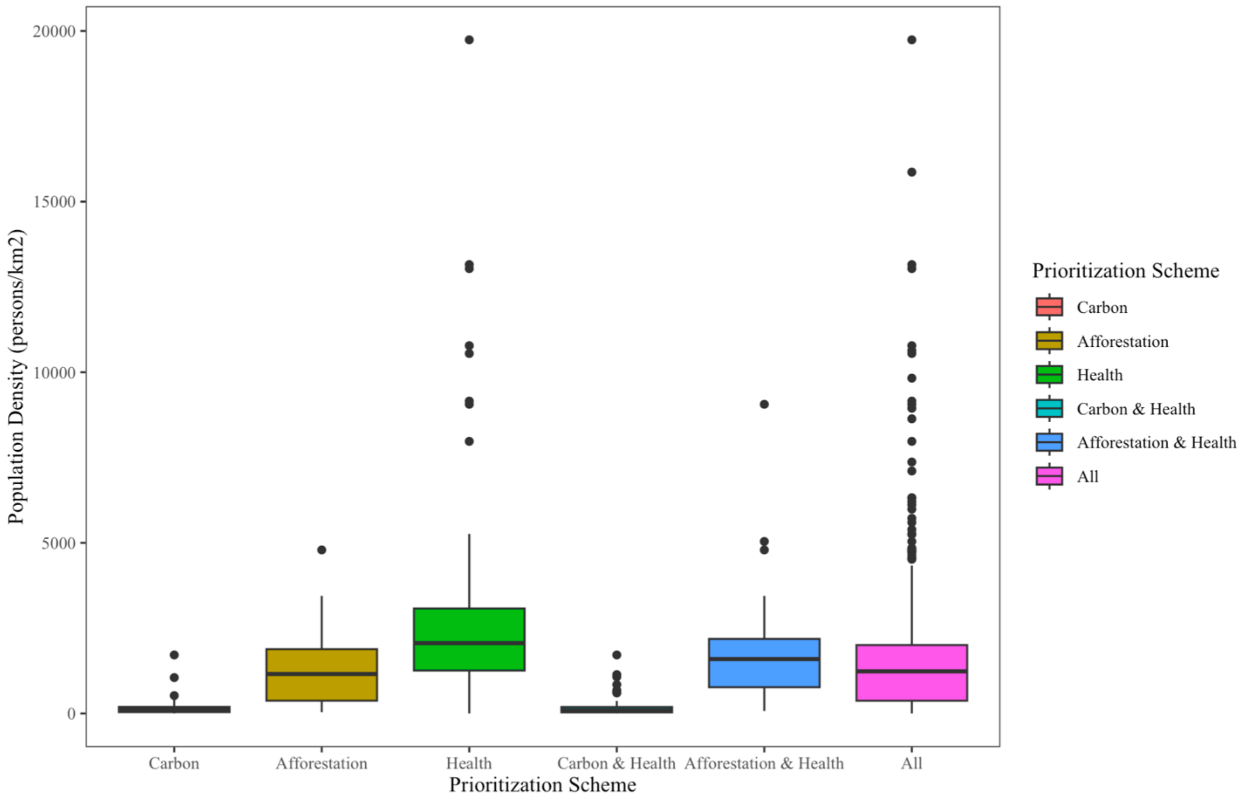

Figure 14. Box plots of population density for the top 10% of census tracts in each of the five prioritization schemes and in all 928 census tracts in the study area.

People of Color

Census tracts ranked high in the carbon prioritization scheme and the carbon and health prioritization scheme tended to have lower percentages of People of Color than census tracts ranked high in the afforestation, health, and afforestation and health prioritization schemes (Figure 15). About 75% of the census tracts in the top 10% of the carbon prioritization scheme as well as the carbon and health prioritization scheme had less than 15% People of Color. By contrast, close to half of the census tracts in the top 10% of the afforestation prioritization scheme had at least 25% People of Color. Likewise, 25% of census tracts in the top 10% of the health prioritization scheme as well as afforestation and health prioritization scheme have more than 40% People of Color.

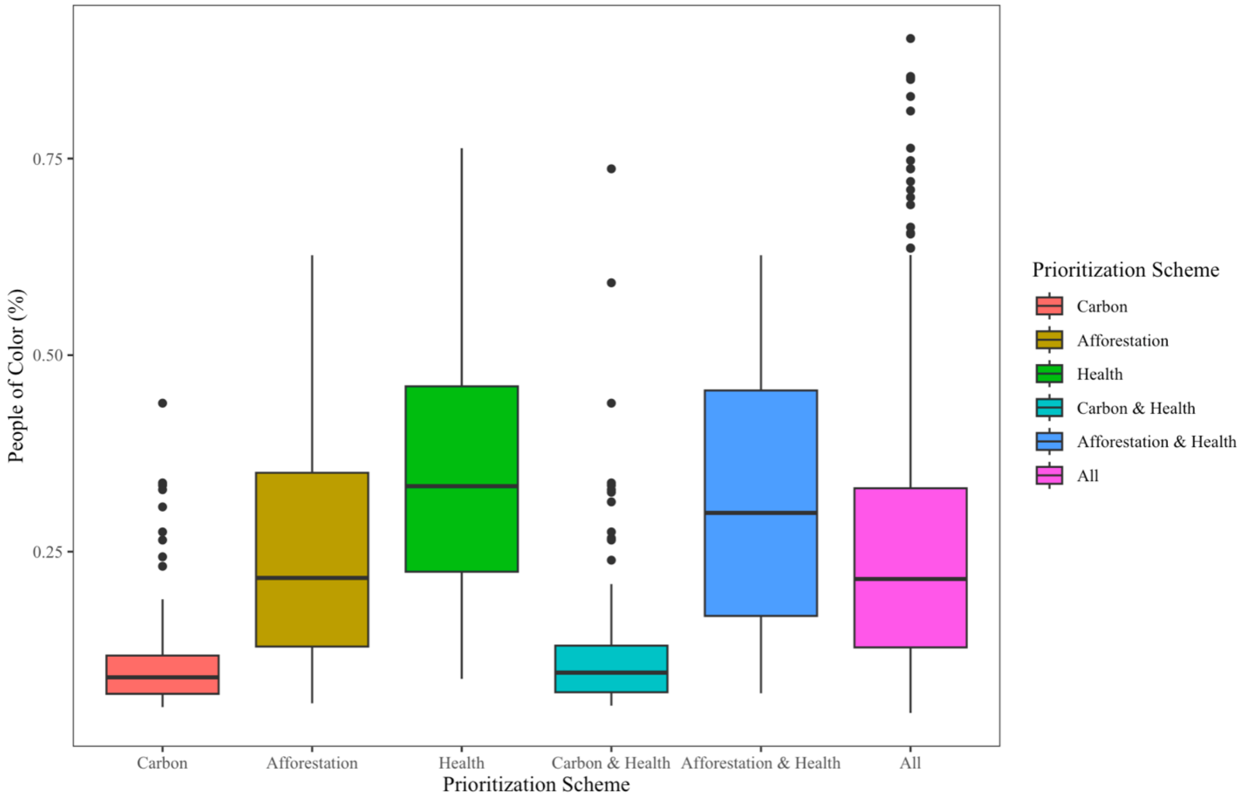

Figure 15. Box plots of percent People of Color for the top 10% of census tracts in each of the five prioritization schemes and in all 928 census tracts in the study area.

Discussion

Climate change is already affecting people, ecosystems, and economies around the world (Masson-Delmotte et al., 2019) and the adverse health impacts of climate change are rising (Romanello et al., 2021). Limiting warming to 1.5 °C above pre-industrial levels is technically possible, but will require swift, unprecedented transitions across all sectors (Masson-Delmotte et al., 2019). Despite the urgent need to address the climate crisis, the financial and human resources for mitigating climate change and addressing environmental health disparities are limited (Gilbert, 2011; McCarthy et al., 2012; Soulé & Simberloff, 1986). Limited resources force land managers and policymakers to prioritize action to achieve the largest return for any investment (Raymond et al., 2017). Returns must be measured with respect to one or more objectives (i.e., that define what outcomes are maximized or minimized; Game et al., 2013). For example, when prioritizing areas where afforestation should occur, objectives may be to reduce urban heat islands to address health disparities (Wiesel et al., 2021), increase carbon sequestration to mitigate climate change (Fargione et al., 2018), and increase green space to improve recreational opportunities (Sikorska et al., 2020). While objectives are fundamental for prioritization of management actions, they are often not explicitly articulated (Game et al., 2013). Without clear objectives, effectiveness and efficiency of action cannot be assessed (Game et al., 2013).

Here, we developed a framework for prioritizing areas on the landscape to achieve two management objectives, and, using the Puget Sound region as a case study, we explored the benefits for human health disparities and carbon of explicitly considering co-benefits when developing implementation plans for NCS. In doing so, we illustrate a simple approach for prioritizing deployment of NCS that evaluates the carbon and human health impacts of different prioritization options. Because our approach is simple, straightforward, transparent, can be performed relatively quickly, and uses data that is generally publicly available, it is a useful addition to existing multi-objective tools and approaches, like multi-objective optimization (Venier et al., 2021) and multi-criteria decision analysis (Huang et al., 2011). As such, our framework for prioritizing areas on the landscape to achieve multiple management objectives can help diverse stakeholders better understand the implications associated with and trade-offs between different management objectives prior to embarking on formal, in-depth multi-criteria analyses.

Our findings highlight that varying the objectives of management actions can generate very different spatial patterns of places where management should be prioritized, and these divergent spatial patterns impact the ability of management to achieve specific outcomes. For example, our analysis revealed that census tracts identified as high priority for using green space to address human health disparities occurred largely in urban areas with high cover of impervious surfaces and high population densities. In contrast, ex-urban and rural areas were identified as high priorities as places for carbon sequestration. Because there are relatively high percentages of People of Color in and around metropolitan areas in the Puget Sound region and generally lower percentages of People of Color in rural parts of the region (*Central Puget Sound Demographic Profile*, 2021), any prioritization effort that consistently selects rural or urban areas has ramifications for the communities that benefit from management actions.

Notably, other studies that have developed frameworks for prioritizing management actions based on multiple objectives have also found that varying the objectives of a prioritization of management actions can generate very different spatial patterns of places where management should be prioritized and thereby impact the ability of management to achieve specific outcomes. For example, Robertson et al. (2021) found that prevention of forest conversion should be prioritized in some of the fastest growing counties in Washington State, like Snohomish County, Pierce County, and King County. But these researchers also found that deployment of cropland agricultural pathways, like the use of no-till agriculture, cover crops, and nutrient management should be prioritized in relatively rural, agriculturally focused counties in the state, like Whitman County, Lincoln County, Adams County, and Grant County (Robertson et al., 2021). Likewise, Meerow (2019) found that the spatial distribution of places where green infrastructure should be added in New York City varied depending on which of the six planning priorities (managing stormwater, reducing social vulnerability, increasing access to green space, improving air quality, reducing the urban heat island effect, and increasing landscape connectivity) was included as the objective of the prioritization. Studying a particular region of the Swiss Alps, Ramel et al. (2020) found that the spatial distribution of places that should be protected to conserve biodiversity differed from the spatial distribution of places that should be protected to safeguard ecosystem services. These findings as well as our findings lead to the same conclusion: being intentional and explicit when defining management objectives is crucial.

Similar discrepancies in the spatial distribution of places where management should be prioritized to maximize different objectives is possible in other regions of the world, as well. For example, inhibiting deforestation (Schwartzman et al., 2000; Soares-Filho et al., 2006; Werth & Avissar, 2002) and protecting watersheds (Soares-Filho et al., 2006) are key conservation objectives for the Amazon Basin. While forested areas generally fall within protected areas in the Amazon Basin, the headwaters of watersheds often extend outside protected areas (Soares-Filho et al., 2006). As a result, prioritizations aimed at supporting the management of protected areas in the Amazon Basin help prevent conversion of forested areas to non-forest uses, but do not effectively protect watersheds (Soares-Filho et al., 2006). Similarly, protecting coral reefs and stimulating economic activity by promoting tourism are primary management objectives for the Great Barrier Reef Marine Park Authority (GBRMPA) and Queensland Parks and Wildlife Service (QPWS) in Australia (Harriott, 2004). Because 85% of tourism in the Great Barrier Reef is geographically concentrated in and around the Cairns and Whitsundays areas, these areas are the focus for tourism management (Harriott, 2004). But, because these areas only cover about 7% of the Marine Park, some areas that are high priority for conservation of coral reefs exist outside of these two areas (Harriott, 2004). Therefore, prioritizations that aim to enhance tourism and support the livelihoods of individuals living and working in these areas may prioritize management of coral reefs in the Cairns and Whitsundays areas. But prioritizations that aim to protect coral reefs in the Great Barrier Reef as a whole may be more efficient at protecting corals but relatively inefficient at promoting tourism and safeguarding the livelihoods of individuals working in the tourism industry.

Our findings also reveal that management actions aimed at conserving natural resources may not efficiently address the needs of people in general, or the needs of more vulnerable populations (e.g., People of Color). For example, when we prioritized census tracts with the objective of maintaining carbon storage, high priority areas were generally in parts of the region where population density is relatively low and there are relatively few People of Color. For comparison, when we prioritized census tracts based on the potential to improve health through exposure to green space, high priority areas were generally in more developed areas where population density is relatively high and there are relatively more People of Color. Consequently, fewer people would confer health benefits from the green space that could be protected based on the carbon prioritization and, likewise, a relatively small fraction of people benefiting from the green space would be People of Color. Ultimately, these findings underscore the need to carefully craft management objectives that address acute needs of local communities, like the need to reduce adverse health outcomes and address environmental health disparities. As such, our findings add to decades-long calls for the integration of ecological and social outcomes in natural resource management, health policy, and other related fields (Bennett et al., 2017; de Snoo et al., 2013; Endter-Wada et al., 1998; Kareiva & Marvier, 2003; Mascia et al., 2003; Sandbrook et al., 2013).

Because the data used in our analysis is publicly available, our methodology could be tailored to specific geographic areas, goals, and spatial resolutions. While we used census tracts as our spatial units of analysis, there is a wide variation in land area among census tracts, with larger tracts in areas with lower population densities, making this unit of analysis too coarse for some purposes and potentially introducing systematic biases in some aspects of the analysis. Further, the spatial resolution of census tracts may be insufficient for fine-scale planning purposes, and additional smaller-scale prioritizations may need to be developed at the census block scale, or potentially an even smaller scale. While we acknowledge that data from the American Community Survey, can have inherent limitations and biases (Warren, 2022), the spatial extent and availability make them a useful dataset for many planning efforts. Further, we have made a number of choices about what data layers to use in these analyses and whether to standardize data by area or population. Each of these represents an important opportunity to extend or modify the basic framework introduced here.

Additionally, future researchers looking to employ our multi-objective prioritization framework should carefully reflect on the assumptions and assertions inherent in our methodology; in some cases, it may be appropriate to adjust the methodology to more accurately prioritize areas where interventions should be implemented to achieve specific management objectives. For example, our approach for prioritizing census tracts based on the potential to augment carbon sequestration through afforestation assumes that afforestation is feasible anywhere there is fine vegetation (e.g., grasses), medium vegetation (e.g., shrubs and bushes), or impervious surfaces that are not buildings (e.g., roads, parking lots, and sidewalks). Further, our approach assumes that afforestation is not feasible where there are buildings, water, or coarse vegetation (e.g., trees). This assumption is incorrect, as numerous socio-ecological factors can affect the feasibility of afforestation (Brancalion & Chazdon, 2017) and afforestation may not be feasible above certain elevations (Malanson & Fagre, 2013) or in areas with less precipitation (Farley et al., 2005). Similarly, our approach for prioritizing census tracts based on carbon storage assumes that all types of coarse vegetation within the Puget Sound region sequester and store carbon at the same rate. Of course, this is incorrect (Gray et al., 2016; Harmon et al., 1986;

Malanson & Fagre, 2013; Waring & Franklin, 1979). Rather, the rate at which different forests and trees store and release carbon is determined by the availability of abiotic resources (e.g., climate, topography, soil type) as well as biotic interactions (e.g., species composition) (Gray et al., 2016; Harmon et al., 1986; Malanson & Fagre, 2013; Waring & Franklin, 1979). Future research could refine our methodology to address these many limitations.

Undoubtedly, addressing the climate crisis swiftly and effectively is critical to the wellbeing of the planet and humanity (Masson-Delmotte et al., 2019). Deployment of NCS can contribute significantly to this effort (Griscom et al., 2020). Further, considering the co-benefits of NCS is highly strategic as it allows decision-makers to advance multiple objectives simultaneously and use limited time and financial resources more efficiently (Raymond et al., 2017). Our framework provides decision-makers with opportunities to consider the health co-benefits of NCS and incorporate human wellbeing and equity into planning processes that might otherwise only consider the carbon benefits of NCS. Further, our framework for prioritizing areas on the landscape to achieve two management objectives provides a straightforward, simple, transparent, and systematic approach to multi-objective prioritization, and is easily tailored to different data sets, geographic regions, outcomes, and management actions.

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