The Sustainable Landscape Health Assessment

A multidimensional ecosystem health assessment tool for the Santa Cruz Mountains

A Report for the Santa Cruz Mountains Stewardship Network

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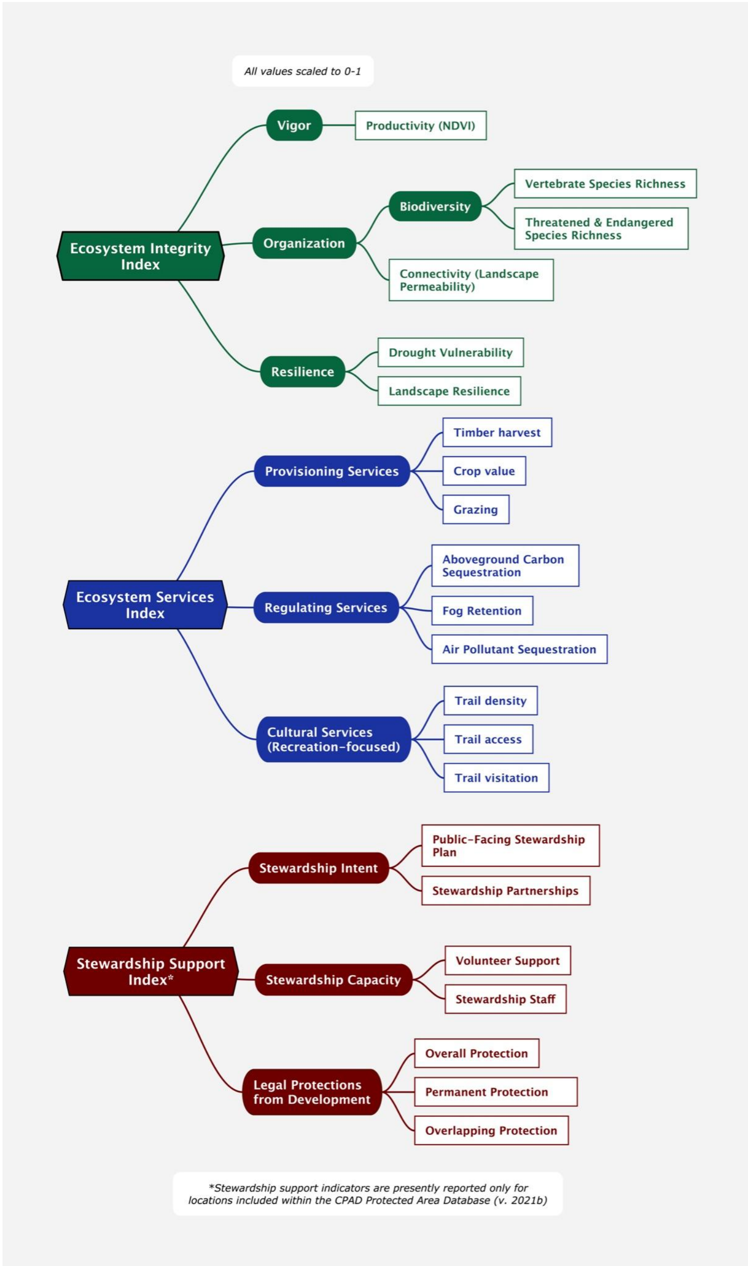
Table of Contents

Executive Summary

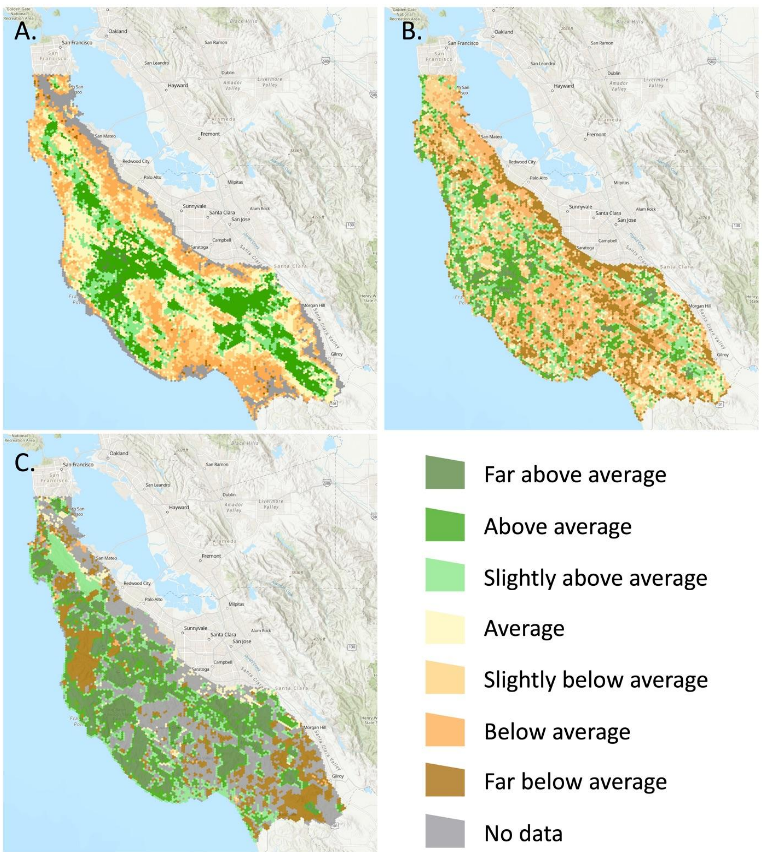
The Sustainable Landscape Health Assessment (SLHA) is a social-ecological decision-support framework for the protected and open-space landscapes within the Santa Cruz Mountains Bioregion (SCMB). The SLHA was designed collaboratively with the Santa Cruz Mountains Stewardship Network (SCMSN) for the SCMSN Digital Atlas, an online shared geospatial library of regional landscape health available to Network members. It is also shared publicly, through the Conservation Land's Network Explorer Tool.

The goal of the SLHA is to advance understanding of conditions within the entire landscape encompassed by Network members, and at the same time recognize that ecosystem health depends on both ecological and social components and processes. Specifically, we sought to design an assessment that recognizes and values diverse definitions and components of landscape health, and helps generate more insights into how people positively contribute to ecosystem health (Figure 1). Rather than a single rollup score, we present landscape health as a series of three lenses, or dimensions, through which the landscape can be viewed. Each lens provides a unique view of landscape health –essentially, one based on a definition of health "for nature" (ecosystem integrity), one based on health "for people" (ecosystem services), and one that represents, in a preliminary way, the stewardship and management of that landscape (stewardship supports).



The assessment has three dimensions: **ecosystem integrity** (EI), **ecosystem services** (ES), and **stewardship supports** (SS). Metrics that relate to each of these dimensions are organized by sub-frameworks specific to each dimension. In the case of EI and ES, we utilize well-established frameworks already used to assess ecosystem integrity and ecosystem services. For SS, we did not find examples of ecosystem health assessment that incorporated the inputs of human agency to ecosystem health, so we crafted this dimension based on available data and our understanding of the factors that contribute to a land management organization's ability to care for the landscape. This framework is offered as a preliminary attempt to integrate across these distinct but complementary dimensions, and it is important to note that the metrics we present within each sub-framework are not comprehensive.

Relative scores for each of these dimensions (and the metrics that comprise them) provide a baseline assessment of the health of habitats and the levels of services provided by open spaces across the region (Figure 2). The results of the SLHA highlights areas where ecosystems have the highest integrity, are providing important ecosystem services, and where attention and investment is being made on the landscape. It also reveals potential opportunities for greater attention and/or investment to improve the health of the landscape. One such opportunity may be the southeastern portion of the SCMB, which has high ecosystem integrity value but low stewardship support value. Another area that may benefit from additional attention is the north coastal region, which has high ecosystem service value but lower values in ecosystem integrity and stewardship support. This region is crucial for farming and ranching and requires mitigation of water pollution and support for the survival of endangered fish and amphibian populations.



The SLHA provides a preliminary decision-support framework and dataset that land managers can use to prioritize management decisions (independently and collaboratively) and to support communications with partners, funders, and the general public.

For more information on the SLHA, please email kellychauvin@stanford.edu.

Framework Design

Characterizing the diversity of a landscape and its stewards for collaborative planning and management
A respect and appreciation for the diverse values that land managers hold for the land and the various ways they care for it is a shared and central value of the SCMSN. Network members have long recognized that this diversity contributes to the resilience of ecosystem health, and that existing conservation decision support tools often failed to capture this diversity among stewarded lands, much less qualitatively or quantitatively characterize it. In 2018, the Network was awarded a grant from the Bechtel Foundation to design an assessment tool that could advance understanding of conditions within the entire landscape encompassed by Network members, while recognizing that ecosystem health relies on both ecological and social components and processes. The goal was to create an assessment that acknowledges and values diverse people and cultural practices as integral components of all ecosystems and conservation efforts, generating more insights into how landscape-scale planning and coordination can contribute positively to ecosystem health.

Through a survey and a workshop, we developed a sense of what the network members wanted. Network members felt that having a shared baseline understanding of landscape health across the entire region was essential, but also that this baseline definition of "health" needed to be relevant to the diversity of perspectives that stewards possess on the work they do to care for their lands . Many spatial datasets already existed for at least some of the region, including maps for wildlife connectivity, fire risk, and other conservation or socially-focused targets, but these had not been combined in any analytical way. Through a review of the literature of ecosystem health assessments, we evaluated several models with ecological and social variables, and ultimately settled on three lenses on the landscape, EI, ES, and SS, as they related most to the aspects of landscape health identified by network members as most important.

The inter-related concepts of ecosystem integrity, ecosystem services, and stewardship supports provide three lenses to view the landscape that relate to the goals towards which they are managed: for biodiversity conservation and to equitably serve human populations, and to assess our stewardship ability to sustain these goals in the Anthropocene.

Ecosystem integrity (EI) is a way of describing whether a landscape represents a complex and functioning ecosystem, with a thriving community of organisms. Often it is characterized for a disturbed/restored landscape in reference to a comparable "natural" site, but it can also be thought of in a more theoretical framework of whether the system reflects natural evolutionary and ecological processes. Human activities are generally included in EI assessments only in their capacity to cause an overall reduction in integrity.

Ecosystem services (ES) are the ways in which nature provides for us. As animals, we require oxygen to breathe and cannot produce our own energy from sunlight, therefore we have a fundamental need for plants. The many ways in which nature and natural processes meet our physical, material, environmental, emotional, cultural, spiritual, and other needs are characterized into three groups of **provisioning, regulating, and cultural** ecosystem services.

Stewardship supports are the regulatory, financial, and infrastructural tools that exist to support ongoing stewardship activities on the landscape. Human stewardship is not typically accounted for in landscape health assessments, and yet it is understood to be a powerful process for improving ecosystem integrity and increasing ecosystem services (find references). However, it is difficult to measure because 1) what constitutes stewardship is itself difficult to define, and 2) stewardship occurs on the landscape by many different actors working at different scales and at different times. The landscapes in this study, of the Santa Cruz Mountains, have been actively utilized and stewarded by many different humans for likely tens of thousands of years. The methods of stewardship undertaken by Native Californians active in this region was drastically different, but perhaps no less active, than that of the colonizers. The present landscape reflects the landscape management of the times since European arrival, but the future landscape may reflect a return to methods of stewardship that are known to be more aligned with the sustainable management of our state's unique biodiversity by Native Californians. It is imperative that we understand where and when and how stewardship occurs, and bear witness to the fruits of this work, if we are to safeguard ecosystem integrity and ecosystem services in the future.

The assessment is hierarchical, with sub-levels combining to higher-order values. All roll-up indices and variables are presented as relative values (0-100%). The three roll-up scores, EI, ES, and SS, cannot be combined, as they are non-equivalent concepts. The following sections detail how all variables and roll-up scores were developed.

Importantly, this is a prototype. Here are some flaws I am aware of:

- A trend in NDVI may not be the ideal way to measure ecosystem productivity and may vary in its efficacy among habitats
- Ecosystem services are skewed towards atmospheric ecosystem services (CO_2 sequestration, fog propagation, air pollutant sequestration)
- Cultural services is primarily focused on recreational value

Despite these shortcomings, the assessment still provides a way to look at the Santa Cruz Mountains landscape that allows network members to examine differences in how well different locations are meeting stewards' goals.

1. ECOSYSTEM INTEGRITY (EI)

Ecosystem integrity is the ability of an ecological system to support and maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region (Theobald 2013). High integrity refers to a system with natural evolutionary and ecological processes, and minimal or no influence from human activities (Angermeier and Karr 1994; Parrish et al. 2003). The Vigor-Organization-Resilience (or VOR) framework is one approach to assessing EI, by measuring the ability of an ecosystem to maintain its **vigor** (a measure of energy moving through the system) and **organization** (a measure of the diversity and complexity of the biotic community) over time and in the face of external stress (**resilience**) (Costanza and Mageau 1999; Rapport et al. 1998).

ECOSYSTEM INTEGRITY INDEX

$$\text{Ecosystem Integrity Index} = (\text{Vigor} + \text{Organization}_s + \text{Resilience}_s)/3$$

The **Ecosystem Integrity Index** is a measure of the health of natural lands within the region along three dimensions: Vigor (V), Organization (O) , and Resilience (R). These components are described in detail in the sections below.

1.1 VIGOR

$$\text{Vigor} \approx \text{Productivity} \approx \Delta \text{NDVI}_s$$

Vigor is a measure of the base level of energetic inputs to a system, generally understood as **primary productivity** (in terrestrial ecosystems, this can be understood to be related to the amount of vegetation). In this study, primary productivity is represented by **the change in annual peak NDVI.**

1.1.1 PRODUCTIVITY (NDVI)

The change in "greenness" over time, or the **Normalized Differentiated Vegetation Index (NDVI)** is an indicator of changes in primary productivity on the landscape (Emmett et al. 2019; McManus et al. 2012; Gillespie et al. 2018). The NDVI trend metric is the **mean annual rate of change in peak NDVI** from the Landsat 5-7-8 record (1984-2020). For a timestack of all Landsat observations, mean annual peak NDVI was calculated as the greenest pixel (max NDVI, 30m2 sized pixel) each year. The NDVI trend was then determined as the mean ridge regression slope value for all annual peak NDVI values within each 30m2 pixel. Landsat data were filtered for clouds and shadows and calibrated for multi-sensor comparison prior to use. All preprocessing and NDVI trend detection steps were run in Google Earth Engine using this script.

A positive trend indicates an increase in vegetation growth over time, and a negative trend indicates a loss in productivity. Land-use changes, climate change, succession, and fire cycles can all influence productivity and NDVI trends. A positive NDVI trend is considered as an increase in productivity, and therefore vigor. Note that this approach does not consider whether a more vigorous system constitutes an 'improvement' to the ecosystem, just that there is generally an increase in the amount of vegetation present. Future analyses should consider whether NDVI or NIRv would be a better estimator of primary productivity, and possibly additional components of vigor, such as insect populations and other indicators for the base of trophic food webs.. NDVI trend were scaled to 0-1 to reflect relative differences across the landscape.

Data Source:
Landsat-5-7-8 imagery courtesy of the U.S Geological Survey

1.2 ORGANIZATION

Organization Index = (Biodiversity$_s$ + Connectivity$_s$)/ 2

Organization refers to the composition and structure of species within ecosystems and the relationships between them. In this study, an **index of organization** combines metrics of **biodiversity** (vertebrate species richness + T&E species richness) and **habitat connectivity**, which indicates how well species in a given location may move or disperse into other natural landscapes around them.

1.2.1 BIODIVERSITY

$$\text{Biodiversity} = (vsr'_s + vsr\_rare'_s) / 2$$

Biodiversity can be measured in many ways. Here we combine a metric of overall diversity (**vertebrate species richness, vsr**) with a metric of rarity (**threatened and endangered vertebrate species richness, vsr_rare**) based on observations of terrestrial vertebrates from four biodiversity databases. Data were obtained from GBIF, eBIRD, and CNDDB from 1970 - 2020, and filtered for quality and spatial accuracy (80 m). Areas of no observations are shown as no data, as these data are occurrence-only. Data were highly right-skewed (many locations of no observations), so data were transformed (log(x+1)) and scaled prior to utilization in model.

1.2.1.1 Vertebrate Species Richness (vsr)

Terrestrial **vertebrate species richness** is an indicator of biodiversity and was calculated as the sum of all cleaned species observations (1970-2020, filtered for spatial accuracy and quality) per hexagon grid cell. CNDDB Data from September 2020 were downloaded via RareFind 5 and filtered to vertebrates seen more recently than 1970, with an accuracy of 80m and presumed extant. Bird data were excluded from the GBIF search, as all GBIF bird records are also included in eBird data, typically with more attributes. eBird is a global database of bird observations, powered by citizen-science observations. The eBird database is updated monthly, and available online. We used the preprocessing filtering routine from Johnston et al. 2021), using the *auk* package in R (Strimas-Mackey et al. 2017).

Data Sources:

Global Biodiversity Information Facility (GBIF). Derived dataset GBIF.org (12 December 2022) Filtered export of GBIF occurrence data https://doi.org/10.15468/dd.vzda35

California Department of Fish and Wildlife. 2020. California Natural Diversity Database search of RareFind5. Accessed September, 2020. https://wildlife.ca.gov/Data/CNDDB/Maps-and-Data#lt-43018407-rarefind-5

eBird. 2020. eBird: An online database of bird distribution and abundance [web application]. eBird, Cornell Lab of Ornithology, Ithaca, New York. Available: http://www.ebird.org. (Accessed: September, 2020).

1.2.1.2 Threatened and Endangered Species Richness (vsr_rare)

Observations of terrestrial threatened and endangered species are an indicator of high biodiversity and ecological organization. Records are from the CNDDB database only, identified by flags for federally listed threatened and endangered species, making this a conservative estimate of vsr_rare. Areas of no observations are shown as no data, as these data are occurrence-only.

Data Source:

California Department of Fish and Wildlife. 2020. California Natural Diversity Database search of RareFind5. Accessed September, 2020. https://wildlife.ca.gov/Data/CNDDB/Maps-and-Data#lt-43018407-rarefind-5

1.2.2 CONNECTIVITY

Connectivity = Landscape Permeability$_s$

Connectivity is the ability of landscapes to act as a conduit for animal movement and genetic flow. These data show the level of **landscape permeability** for plants and animal species who move only through natural landscapes, and was shared with permission by Together Bay Area and the Nature Conservancy for inclusion in this assessment.

Data are derived from the Omniscape circuit-theory landscape connectivity model, developed by the Nature Conservancy (2016). The landscape is scored for its ability to allow for movement, which is a function of the features of the landscape itself (whether it is a natural land patch or a developed/disturbed landscape) as well as what features it is in proximity to (for a given location, having a nearby protected area would allow for more movement whereas a nearby highway would restrict it. These data were provided at 90m resolution, as a classified raster with four classes: 1 -no connectivity to surrounding landscapes, 2- channelized/fragmented landscapes with a few movements possible, 3- intensified connectivity with many movements possible or 4-diffuse connectivity with no movements restricted in any direction. A higher value means more natural connectivity to surrounding landscapes. Lower scores mean a more fragmented landscape/less connectivity. Data were scaled but remain ordinal.

Data Source:
The Nature Conservancy, 2016. Omnidirectional Circuitscape "OmniScape", a custom TNC product produced for Together Bay Area (not available for download). Learn more about this dataset at OmniScape Explorer

1.3 RESILIENCE

Resilience = (Landscape Resilience$_s$ - Drought Vulnerability$_s$) /2

Resilience is a system's capacity to maintain structure and function in the presence of (external) stress. In this study, we utilize an integrated measure of resilience that combines an existing **landscape resilience score** (based on topological, land use, and connectivity characteristics, TNC 2019) and a known vegetation stress in this region, **vulnerability to drought** (veg_risk).

A future analysis could include and integrate over a larger number of specific landscape vulnerabilities (e.g., drought, fire, flood, temperature thresholds).

1.3.1 LANDSCAPE RESILIENCE

Landscape resilience = human modification and microclimatic diversity

Landscape resilience (Resil_scaled) is a combined measure of local microclimatic diversity and the level of human modification. High microclimatic diversity and low human modification provide species with connected, diverse climatic conditions that they will need to persist and adapt to changing regional climates. This metric was developed by The Nature Conservancy as part of their Resilient Sites program. The inputs to landscape resilience are landscape diversity (the variety of landforms), elevation range, the diversity and configurations of ecosystems within 100 ac.(40.4 ha), and local connectivity (based on human modification). A future analysis of landscape resilience could utilize finer scale data on topography and vegetation that is provided through the Fine-Scale Vegetation Mapping effort being undertaken in the region.

Data Source:
The Nature Conservancy, 2016. Omnidirectional Circuitscape "OmniScape", a custom TNC product produced for Together Bay Area (not available for download). Learn more about this dataset at OmniScape Explorer

1.3.2 DROUGHT VULNERABILITY

Drought Vulnerability = Climatic Water Deficit

Drought vulnerability (veg_risk), is an estimate of the extent to which a stand of natural vegetation is approaching the edge of their climatic 'comfort zone', using the climate variable **Climatic Water Deficit (CWD)**. This approach was developed by the Conservation Lands Network 2.0 by utilizing vegetation-specific CWD values obtained from mid-century scenarios of climate change (USGS California Basin Characterization Model) and vegetation data (Eveg data rasterized to 5m pixels; full details available at www. bayarealands.org).

The 95th percentile of CWD values for each vegetation type was used as a proxy for a given stand's upper tolerance limit for CWD. Stands with CWD values beyond the 95th percentile are assumed to be at very high risk of drought. Stands with CWD values approaching the 95th percentile (based upon their CDF within the 10 county Bay Area) are assumed to be at high risk. Stands with lower risk classes can be interpreted as having a greater capacity to absorb the impacts of drier climates. For further information, please refer to the Conservation Lands Network 2.0 Report (2019).

Data Source:

Bay Area Open Space Council. 2019. *The Conservation Lands Network 2.0 Report.* Berkeley, CA.

Citations

Theobald, D.M. (2013). A general model to quantify ecological integrity for landscape assessments and US application. Landscape Ecology, 28, 1859-1874. doi:10.1007/s10980-013-9941-6

Costanza, R., & Mageau, M. (1999). What is a healthy ecosystem? Aquatic Ecology, 33, 105-115. doi:10.1023/A:1009930313242

Rapport, D.J., Costanza, R., & McMichael, A.J. (1998). Assessing ecosystem health. Trends in Ecology & Evolution, 13(10), 397-402. doi:10.1016/S0169-5347(98)01449-9.

Angermeier, P.L., & Karr, J.R. (1994). Biological integrity versus biological diversity as policy directives: Protecting biotic resources. BioScience, 44(10), 690-697. doi:10.2307/1312512

Parrish, J.D., Braun, D.P., & Unnasch, R.S. (2003). Are we conserving what we say we are? Measuring ecological integrity within protected areas. BioScience, 53(9), 851-860. doi:10.1641/0006-3568(2003)053[0851:AWCWWS]2.0.CO

McRae, B.H., K. Popper, A. Jones, M. Schindel, S. Buttrick, K. Hall, R.S. Unnasch, and J. Platt. 2016. Conserving Nature's Stage: Mapping Omnidirectional Connectivity for Resilient Terrestrial Landscapes in the Pacific Northwest. The Nature Conservancy, Portland Oregon. 47 pp. Available online at: http://nature.org/resilienceNW June 30, 2016.

2. ECOSYSTEM SERVICES (ES)

Ecosystem services are the life-sustaining benefits provided to humans by ecosystems, such as clean air, clean water, protection from floods and erosion, food to eat, healthy bodies and minds, and places that are meaningful to humans from individuals to entire societies (Millennium Ecosystem Assessment, 2005). Ecosystem services are frequently organized into provisioning, regulating, and cultural services. **Provisioning services** include all products directly obtained from ecosystems, including food, water, and materials such as fiber and timber. **Regulating services** are benefits obtained from the regulation of ecosystem processes that are key inputs to human lives and enterprises (e.g., soil formation, nutrient cycling, water filtration and cycling). **Cultural services** are the non-material benefits people obtain from ecosystems (e.g., aesthetic values, recreation and ecotourism, physical and mental well-being, culture, spirituality).

ECOSYSTEM SERVICES INDEX

$$ESI = (Provisioning_s + Regulating_s + Cultural\ Services_s)/3$$

The **Ecosystem Services Index (ESI)** is a combined measure of the level of provisioning, regulating, and cultural services provided by natural landscapes within the SCMB, with services described below. We acknowledge that these characterizations of ecosystem services are incomplete and offer them as a starting place. Moreover, ES should not only be evaluated for their value to a subset of existing users and to the general population, but with a special emphasis placed on how and where disadvantaged communities and user groups are being served, and where that service could increase.

2.1 PROVISIONING SERVICES

Provisioning services are products directly obtained from ecosystems (e.g., food, fiber, timber). In this study, we include **timber harvest, grazing yields, and agricultural (crop) value** as provisioning services, as these are identified as important industries to local open-space oriented economic activities. Future additions might include water yield/groundwater recharge and pollinator services. Full details of provisioning services can be found here.

$$Provisioning = Timber + Grazing + Mean\ Crop\ Value'_s$$

2.1.1 TIMBER VALUE

Timber has an annual market value of roughly $8 million for the three counties comprising the Santa Cruz Mountains (from timber harvest info for 2020-ref). Local timber companies such as Big Creek Timber and Redwood Empire have helped to pioneer sustainable harvest practices, such as selective logging, that have influenced state timber policy, and have helped to sustain a local forestry workforce with specialized knowledge of this unique ecoregion. Lands that are harvested for timber must have on file a timber harvesting plan, a document provided to the State which outlines what is to be harvested and how, and by whom, among other things. Non-identifying location information is available for all timber harvest plans, as a geospatial database through CAL FIRE. We only have information on the location that the harvest plan applies to, not the number or locations of the specific trees harvested within that location (note that all tree harvesting in the Santa Cruz Mountains is selective). We also do not have information on the value of the timber extracted from locations. Therefore, in this study, we use only a binary metric of **recent timber harvest** , as locations with a timber harvest plan (completed/approved NTO or THP, or filed NTMP from 2015-2020).

Data Source:
California Department of Forestry and Fire Protection. 2022. Timber Harvest Plans (THPs) - CAL FIRE. Accessed Jan 2021.
https://gis.data.ca.gov/maps/04777bf6e6ce4b4d93298f4e3ba88d7f/about

2.1.2 GRAZING VALUE

Grazing is an important activity in the Santa Cruz Mountains. Conservation grazing is utilized for invasive species management and native grassland restoration, as well as contributing to the local livestock industry (SCVOSA 2013). The Farmland Mapping and Monitoring Project (FMMP) has identified roughly 500 mi2 as potential grazing lands throughout the region, however, only a small number of them have actually been grazed. Using this layer as a starting point, we overlaid confirmed grazing lands from our network partners and removed areas confirmed by network partners to have no grazing. These data are therefore unevenly accurate and should be interpreted with caution.

Data Sources:
California Department of Conservation. 2016. Farmland Mapping and Monitoring Program - Grazing Land. Accessed online March 2019, available here.
Santa Clara County Open Space Authority. 2013. Grazing Management Policy. Accessed online June 2020 here.

2.1.3 AGRICULTURAL VALUE

Agriculture is a local industry of roughly $1B annual market value. We derived **mean crop values** from county agricultural commissioner crop reports (2015-2020) for Santa Clara, Santa Cruz, and San Mateo counties. Crop types within each county's reports were cross-walked to the crop categories in a statewide, comprehensive geospatial assessment of agriculture land use for 2016, prepared by Land IQ, LLC and provided to the California Department of Water Resources (DWR) and other resource agencies, and was shared with us by Together Bay Area (documentation here). Crosswalking steps can be viewed here. **Crop values** were then summarized for each hexagonal grid cell as a mean value. A future assessment of local food services should include more dynamic metrics such as the distribution and impact of farmers markets, farm box subscriptions, and an estimate of how much produce stays local vs leaves the area. Mean crop value was transformed and scaled.

Data sources:
County of San Mateo. Agricultural Crop Reports. 2015-2020. Accessed online November 2020.
https://www.smcgov.org/agwm/agricultural-crop-report

County of Santa Clara. Annual Crop Reports. 2015-2020. Accessed online November 2020.
https://ag.sccgov.org/2010-2019-crop-reports

County of Santa Cruz. Annual Crop and Livestock Reports. 2015-2020. Accessed online November 2020.
https://www.agdept.com/AgriculturalCommissioner/AnnualCropandLivestockReports.aspx

2.2 REGULATING SERVICES

Regulating services are benefits obtained from the regulation of ecosystem processes (e.g., soil formation, nutrient cycling, photosynthesis). In this study, we include **aboveground carbon storage**, **air pollutant sequestration**, and **fog retention by vegetation** as our suite of regulating services**.** Future assessment of regulating services should include additional services such as belowground carbon sequestration, sediment retention/erosion control, water quality protection/enhancement, and flood control, and the identification/development of an appropriate sub-framework for a holistic view of regulating services.

$$\text{Regulating} = \text{Carbon Sequestration}_s + \text{Fog Retention}_s + \text{Air Pollution Sequestration}_s$$

2.2.1 ABOVEGROUND CARBON STORAGE

The relative amount of carbon held by aboveground living biomass. Aboveground live carbon density was estimated from Landfire data, calibrated with biomass data from numerous sources by Gonzalez et al. (2015), and shared with permission by Together Bay Area. Aboveground live carbon density was measured in megagrams per hectare (Mg/ha) at a 30-meter cell size and was converted to total carbon stock in CO2 equivalents using the conversion factor of 3.67 for woody biomass in the following equation.

Total carbon content (CO2e) = Aboveground carbon density (kg/m2) *900m2/ 1 grid cell * 3.67 (kg CO2e/kg C)

The geodatabase for the carbon stocks can be found here. The BA_AGC raster layer was used.
These data are from 2010 imagery, and an update with more recent imagery would be useful. Future carbon sequestration metrics should include both above and belowground carbon, and provide an understanding of the rate of change of these pools over time.

Data source/citation:

Gonzalez, P., Battles, J. J., Collins, B. M., Robards, T., & Saah, D. S. (2015). Aboveground live carbon stock changes of California wildland ecosystems, 2001–2010. Forest Ecology and Management, 348, 68-77. doi:10.1016/j.foreco.2015.03.040

2.2.2. AIR POLLUTANT SEQUESTRATION

The ability of vegetation (classified as grasslands, shrublands, and canopy) to sequester anthropogenic air pollution, thereby reducing human exposure. A combined index of the relative annual pollution sequestered from 6 pollutants (CO, SO2, NO2, PM 2.5, PM 10, O3) (g/m2).

Vegetation plays a role in maintaining and improving air quality, by sequestering harmful air pollutants directly onto plant surfaces (Nowak et al. 2006, Hirabayashi and Nowak 2016, Gopalakrishnan et al. 2018). We utilized county-level estimates of the **annual dry deposition pollutant sequestration rates** of six air pollutants (CO, SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 in g/m^2) by forests, grasslands, and shrublands determined by Hirabayashi and Nowak (2016) and Gopalakrishnan et al. (2018) using a modified version of the i-Tree Eco model developed by the USDA Forest Service (https://canopy.itreetools.org). These data estimate annual dry deposition pollutant sequestration rates in g/m^2 utilizing MODIS-derived estimates of leaf area index (LAI) along with county-level tree, grass, and shrub cover estimates derived from the National Land Cover Database for the year 2010 (Gopalakrishnan et al. 2018, 2019; Nowak et al. 2014; Hirabayashi and Nowak 2016).

We determined a total air pollutant sequestration index for all hexagonal grid cells within the area of analysis as the sum of all six pollutant sequestration rates, which were first scaled to 0-1 to allow for combination. For each pollutant, the grid cell sequestration rate was calculated as the weighted sum of all land cover and county specific sequestration rates by the area of each cell in each land cover class (see equation below).

$$\text{Total Sequestration Rate}_i \ (g/m^2) = \sum(SR_{ijk} * \text{land area}_{ijk})/\text{area}_i$$

i =grid cell
j = one of three land cover types (forests, shrublands, or grasslands)
k = county (San Mateo, Santa Cruz, Santa Clara)

Please note that canopy pollutant values in Santa Cruz County are not separated into rural/urban, and that NO2 values in Santa Cruz are categorically lower than adjacent values in Santa Clara and San Mateo County.

Data Sources/Citations:

Gopalakrishnan, V., Ziv, G., Hirabayashi, S., & Bakshi, B. R. (2019). Nature-Based Solutions Can Compete with Technology for Mitigating Air Emissions Across the United States. *Environmental science & technology*, *53*(22), 13228-13237.

Gopalakrishnan, V., Hirabayashi, S., Ziv, G., & Bakshi, B. R. (2018). Air quality and human health impacts of grasslands and shrublands in the United States. *Atmospheric Environment*, *182*, 193-199.

Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. *Environmental pollution*, *193*, 119-129.

Hirabayashi, S., & Nowak, D. J. (2016). Comprehensive national database of tree effects on air quality and human health in the United States. *Environmental Pollution*, *215*, 48-57.

2.2.3 FOG AND LOW CLOUD COVER RETENTION

Fog retention by vegetation is a crucial regulating process in California's coastal ecosystems (*Weathers*, 1999; *Mooney et al.*, 2001, Torregrosa et al. 2016). The presence of fog and low cloud cover (FLCC) during the dry summer months reduces the evapotranspiration stress of plants at the leaf and surface root levels (*Fischer et al.*, 2009; *Baguskas et al.*, 2014, *Katata et al.*, 2010; *Valiente et al.*, 2011), and increases mycorrhizal productivity (*Carbone et al.*, 2013). Fog drip also increases streamflow (*Gurnell*, 1976; *Harr*, 1982). During extreme late summer low streamflow conditions, fog events can result in sufficient fog drip and reduced evapotranspiration to increase streamflow by 200% (*Sawaske and Freyberg*, 2014).

Mean decadal (1999-2009) summertime fog and low cloud cover (FLCC) was used as a proxy for the regulating service of fog retention (Torregrosa et al. 2016). FLCC is calculated as the average FLCC hours per day from an archive of hourly, day and night, June, July, August, and September, 1999 - 2009, GOES (geostationary operational environmental satellite) images collected and processed by the Cooperative Institute for Research in the Atmosphere (CIRA). FLCC data were scaled 0-1.

Data source/citation:

Torregrosa, A., C. Combs, and J. Peters (2016), GOES-derived fog and low cloud indices for coastal north and central California ecological analyses, Earth and Space Science, 3, doi:10.1002/2015EA000119.

2.3 CULTURAL SERVICES

Cultural services are nonmaterial benefits people obtain from ecosystems (e.g., aesthetic values, recreation and ecotourism, cultural diversity). In this study, we include only a subset of cultural values: recreational value via trail density, access to nature as the distribution of trail access points, and park visitation rates using a metric of social media photo popularity.

These are common metrics utilized when assessing the importance of a landscape for human recreation (see Costanza et al. 1997), but do not provide a holistic view of the cultural services that are currently or could be provided by the landscape, as that can only be gained in relationship with the diverse communities who use, have used, or could use, these landscapes (Hernández-Morcillo et al. 2013). While we did not have the sufficient time, knowledge base, or opportunity to address cultural services sufficiently in this assessment, we feel that it is an important and worthwhile endeavor. One possible approach would be to design a community-based process to define a set of community landscape values, following the approach of Alessa et al. (2008) and Hashimoto et al.

(2015) with modifications for the key cultural services of our region, to characterize cultural services within the SCMB.

$$\text{Cultural Services} \approx \text{Recreational Value} = \text{Trail Density}'_s + \text{Access}'_s + \text{Visitation}'_s$$

We utilize a proxy for **recreational value**, **trail density** (km/m3). Trail data was developed for the SCMSN region in collaboration with network partners and regional trail-maintaining organizations. Areas of high trail density are presumed to be of high recreational value, and landscapes with no trails are considered, in this preliminary approach, to be of low recreational value. Even taking the narrow view of trail-based recreational value, this metric could be improved by an analysis of viewsheds. Landscapes that are not directly adjacent to trails often contribute to much of the value to the trail itself. A future assessment of trail recreational value is forthcoming, as a project of the SCMSN (include a link to a small write up and reference), and should be integrated into a second version of this assessment.

2.3.1 TRAIL ACCESS

As a first-pass metric of access to nature, we quantified **access points** as trailheads within 50 ft of any street across the region. Access points were summed for all grid cells, and the relative abundance of access points is displayed

Citation: Santa Cruz Mountains Stewardship Network. 2019. Trail Database of the Santa Cruz Mountains. Data provided by Network members.

2.3.2 TRAIL DENSITY

Trail density is a preliminary proxy for recreational value. Trail data was developed for the SCMSN region in collaboration with network partners and regional trail-maintaining organizations Note that this is available only in the Santa Cruz Mountains.

Citation: Santa Cruz Mountains Stewardship Network. 2019. Trail Database of the Santa Cruz Mountains. Data provided by Network members.

2.3.3 TRAIL VISITATION

Park visitation rates are one indicator of how open spaces are serving human populations. We estimated natural area visitation rates using the InVEST Visitation model, following the methodology of Wood et al (2013), using the mean annual photo-user-days (PUDs) derived from flickr geotagged photographs. We analyzed the PUD for the full range of the database (2005-2017), within all natural landscapes of the Santa Cruz Mountains boundary, at a 90m2 resolution that was further aggregated to the hex grid cells.
Additional details of this method can be found here.

Data source:

Wood, S., Guerry, A., Silver, J. *et al.* Using social media to quantify nature-based tourism and recreation. *Sci Rep* 3, 2976 (2013). https://doi.org/10.1038/srep02976

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3. STEWARDSHIP SUPPORT (SS)

Stewardship support is the term we use to describe collectively the resources, systems and practices that support the land manager in their job as landscape steward. In this context, we define stewardship as being the care of an open space/ natural landscape beyond what is required for its value solely to its legal owner/proprietor, and specifically as care for the landscape to value those who rely upon it but may not have any legal claim to it, including marginalized human populations, non-human beings, and future generations. For this preliminary assessment of stewardship supports, we characterized the supports available to stewards of open-space and public lands within the Santa Cruz Mountains (CPAD, 2021a) in three focus areas: **stewardship intent** (the publicly stated goals for a given landscape), **stewardship capacity** (the people-power to make stewardship happen), and the **legal protections from development** that contribute to a stewardship mandate.

STEWARDSHIP SUPPORT INDEX

Stewardship Support Index = (Intent + Capacity + Protections From Development)/3

The **Stewardship Support Index** is a *preliminary* measure of the resources and supports available to the caretakers of a landscape in their work to steward a landscape in three focus areas: **stewardship intent** (the publicly stated goals for a given landscape), **stewardship capacity** (the people-power to make stewardship happen), and the **legal protections from development** that contribute to a stewardship mandate. Please note that these attributes were assessed only for lands included in the publicly available California Protected Area Database (CPAD, 2021a).

These components are described in detail in the sections below.

3.1 STEWARDSHIP INTENT

Stewardship Intent ≈ Stated Stewardship Intention + Collaborations

An intent to steward the land can be expressed publicly or privately, and may occur at the level of individual to organization. We based our preliminary assessment of stewardship intent on whether an organization's public online presence was indicative of a **stated stewardship intention** to care for lands for ecological integrity or ecosystem services, and evidence for **collaboration** with other stewardship organizations in the region.

3.1.1 Stated Stewardship Intention

A **stated stewardship intention** to care for lands for ecological integrity or ecosystem services was be evidenced by inclusion of relevant language in an organization's mission statement, website, publicly available planning documents, or through the details of their stewardship work on their website and/or Facebook page. This was done at the organization/agency level, as not all individual properties have websites/sufficient online presence.

3.1.2 Collaborations

Peer to peer learning and support is an important resource for land stewards. Collaborating can yield more impactful work, and knowledge sharing around issues and opportunities that stewards face can accelerate good stewardship solutions. In this assessment, steward-to-steward engagement is represented by participation in regional stewardship collaborations, including the Santa Cruz Mountains Stewardship Network, the Golden Gate Biosphere Network (SFPUC Watershed lands and NPS/GGNRA lands- Rancho Corral de Tierra), or evidence of collaboration with other land stewards as evidenced by an internet search. This may not capture all partnerships, and was performed at the organization/agency level, as above.

3.2 STEWARDSHIP CAPACITY

The financial resources and people-hours that are available for stewardship work to be done constitute one set of limits on stewardship. An assessment of budgetary resources devoted towards the somewhat ambiguous work of stewardship was judged to be a potentially too time-consuming request of Network members, and thus our assessment focuses only on the people-power contribution to capacity, as dedicated stewardship staff and volunteers.

Stewardship Capacity ≈ Volunteers + Staff

3.2.1 Volunteers

Evidence of sustained volunteer presence on the landscape, such as the existence of "Friends of … " organizations, a volunteer coordinator role around land stewardship, or a calendar of regular stewardship volunteer opportunities.

3.2.2 Staff

One or more people whose job is at least partially dedicated to caring for the land and/or its inhabitants.

3.3.LEGAL PROTECTIONS FROM DEVELOPMENT

Legal protections from development include measures and strategies designed to safeguard a landscape from human development, and may include lands with title-based protections, conservation easements, and zoning restrictions. In this assessment, we include three types of legal protections from development: title-based, or permanent, protections, conservation easements of varying lengths, and properties protected under the California Land Conservation (Williamson Act). Frequently, a single landscape may be protected by multiple protections, such as both a conservation easement and a title-based protection. We developed an overall index of protection that gives a ranked score based on the amount of overall, permanent, and overlapping protection from development. This assessment utilized the entire SCMSN study region.

Protection from Development ≈ Overall + Permanent + Overlapping Protection

- **Overall protection.** A flattened layer of Williamson, CPAD, and easement protection to represent the maximum coverage of any type of legal protections.

- **Permanent protection.** Areas that are protected with a title based protection (and therefore included in CPAD).
- **Overlapping protection.** Areas that are protected with a multiple protection types (e.g., title and easement)

Data sources:
California Protected Areas Database 2021a. GreenInfo Network. July 2021.
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