Resilient Sites & Connected Landscapes

For Terrestrial Conservation

in Hawaii

Mark Anderson, Analie Barnett,
Melissa Clark, Sam Gon,
Arlene Olivero, John Prince,
and Stephanie Tom

The Nature Conservancy

CRCS CENTER FOR RESILIENT CONSERVATION SCIENCE

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Center for Resilient Conservation Science
The Nature Conservancy
99 Bedford St, 5th Floor
Boston, MA 02111
crcs@tnc.org

For more information, online maps, and datasets visit our website at:
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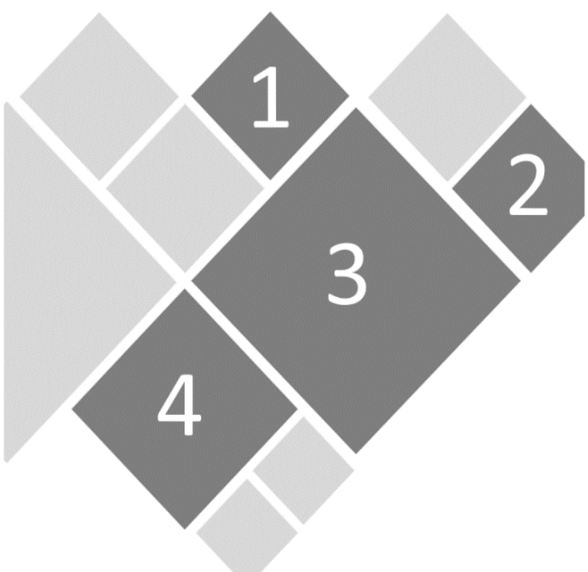

About the Cover:

1. Endemic Kaua'i elepaio (Chasiempis sclateri), Pihea Trail, Kokee State Park, Kauai, Hawaii.© 2012 Ethan Welty for The Nature Conservancy
2. Detail of young (red) frond of endemic amau fern (Sadleria cyatheoides), Pihea Trail, Kokee State Park, Kauai, Hawaii. © 2012 Ethan Welty for The Nature Conservancy
3. View down Wainiha Valley from the Alakai Plateau, on Kauai, Hawaii. © 2012 Ethan Welty for The Nature Conservancy
4. A tour boat is dwarfed by the high cliffs of the Na Pali Coast, Kauai, Hawaii. © 2012 Ethan Welty for The Nature Conservancy

Acknowledgements

This project represents the final piece in a twelve-year, 50 state, collaborative project led by The Nature Conservancy's Center for Resilient Conservation Science. Over the course of project, we engaged over 287 scientists through our geographic steering committees, and we acknowledge that the quality and usability of the results is due to their careful review of the concepts, methods, data sources, and mapped results. We deviated from this model slightly for Hawaii in order to complete the work during a global pandemic. Instead of assembling a large steering committee we worked closely with our Nature Conservancy colleagues in the Hawaii program who provided a similarly high level of review and expertise. Our thanks to Dr. Sam Gon III, the Conservancy's Senior Scientist Cultural Advisor, and Stephanie Tom, the Conservation Information Manager. Sam is a wealth of information on the ecology of the state. He has been a part of the Conservancy for over 30 years, first as the Ecologist for the Hawaii Natural Heritage Program, then as Director of Science for the state, and now as Senior Scientist and Cultural Advisor. Stephanie seems to know everything about every Hawaii dataset. She has acquired or created maps, geospatial data, satellite images, aerial videos, LIDAR, multispectral images, historical maps, and crowdsourced information to show forest recovery, create reference maps, plot new access routes, map natural barriers to ungulates, and map weed invasions. Kudos again to both, we could not have completed this project without their thoughtful help, careful review, and interesting stories.

We gratefully acknowledge and thank Sacha Spector and Danielle Levoit of the Doris Duke Charitable Foundation for support of this work and helpful feedback.

We also extend our thanks to ESRI for making ArcGIS software freely available to The Nature Conservancy. The complicated analysis and resulting beautiful maps in this report are a testament to ESRI's ongoing generosity.

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INTRODUCTION

CHAPTER 1

This report presents the results of a 1-year project to identify and map climate resilient sites across the state of **Hawaii** in the U.S. This work was made possible by a grant from the Doris Duke Charitable Foundation, along with contributions from the
Hawaii Chapter of The Nature Conservancy (TNC). It is part of a set of analyses to identify a comprehensive and connected network of resilient lands across the U.S.

Project History and Scope

TNC has been working for over ten years with support from the Doris Duke Charitible Foundation to identify climate resilient sites in the United States. The Conserving Nature's Stage (CNS) approach has been applied to the U.S. Northeast, Southeast, Great Lakes and Tallgrass Prairie, Great Plains, Rocky Mountains, Desert Southwest, California and Pacific Northwest regions (Anderson and Ferree 2010; Anderson et al. 2012; Anderson et al. 2014a; Anderson et al. 2016a; Anderson et al. 2018a; Anderson et al. 2018b., Anderson et al. 2019, Buttrick et al. 2015). Each of these geographies were analyzed using CNS methods pioneered by TNC's Center for Resilient Conservation Science team led by Dr. Mark Anderson and further refined in each geography by teams of TNC scientists supported by regional Steering Committees. Our goal was to complete this work in Hawaii and add it to the Resilient Sites and Resilient and Connected Networks data for coterminous US

In this project, we expanded the CNS approach to Hawaii, identifying the enduring geophysical drivers of biodiversity and the land characteristics that create resilience, and mapping a suite of places that capture these features across the region. We also identified important pathways that connect these places to allow for dispersal and migration of organisms and natural communities. We developed a blueprint for conservation priorities across this broad region, creating a resilient network that can link to similar networks previously identified the conterminous US and ultimately supporting strategies and investments that enhance the resilience of biodiversity as climate changes.

Hawaii Ecoregion

The boundary of our study area was the Hawaiian High Islands Ecoregional plan, and described in The Nature Conservancy's 1998 ecoregional plan (http://www.hawaiiecoregionplan.info/ecoregion.html). The goal of the assessment was to bring active, protective management to representative, viable, native ecological systems and species of the Hawaiian Archipelago, and sustain the greatest possible complement of native Hawaiian biodiversity into the future.

The following descriptions of the ecoregion boundaries, habitats, physiography, climate and biodiversity is taken directly from the TNC plan:

"The Hawaiian High Islands Ecoregion lies in the north central Pacific Ocean. It is comprised of the ecological systems, natural communities, and species associated with the terrestrial portion of the main archipelago of the Hawaiian Islands (eight major islands and immediately surrounding islets). These islands have a total land area of 1,664,100 hectares (4,062,660 acres). This terrestrial ecoregion excludes the Northwestern Hawaiian Islands (belonging to Hawaiʻi coastal/marine ecoregion) and the surrounding marine environment. The Hawaiian High Islands Ecoregion lies within the Hawaiian Biogeographic Province, which encompasses all of the above ecoregions and occupies the northern portion of the Oceanian Realm.

The Hawaiian High Islands Ecoregion Boundary is defined by the TNC/NatureServe National Ecoregional Map. It is a modification of Bailey's Ecoregions of the United States. The World Wildlife Federation (WWF) recognizes four ecoregions for the Hawaiian Islands (Hawaiʻi Tropical Moist Forest [OC0106], Hawaiʻi Tropical Dry Forest [OC0202], Hawaiʻi Tropical High Shrubland [OC0701], and Hawaiʻi Tropical Lowland Shrubland [OC0702]) (Gon & Olson 1999, Ricketts et al 1998).

The Hawaiian High Islands Ecoregion contains three major habitat types: Tropical Moist Broadleaf Forest, Tropical Dry Broadleaf Forest, and Tropical Grasslands, Savannas & Shrublands. The boundaries of the Hawaiian High Islands Ecoregion correspond to the collective sea-level island boundaries of the main Hawaiian Islands and immediately surrounding islets. There are no contiguous terrestrial ecoregions.

The Hawaiian High Islands Ecoregion is marked by a very wide range of local physiographic settings. These include fresh massive volcanic shields and cinderlands reaching over 4000 m (13,000 ft) elevation; eroded, faceted topographies on older islands; high sea cliffs (ca 900 m [3,000 ft] in height); raised coral plains; and amphitheater-headed valley/ridge systems with alluvial/colluvial bottoms. Numerous freshwater stream systems are found primarily on the older, eroded islands, but also on the wet, windward slopes of even the youngest island, Hawaiʻi (Juvik & Juvik 1998).

The general climate is tropical/subtropical, but with combinations of elevation and orographic rainfall patterns that yield extremely wet (>1000 cm [>400 inches] annual rainfall) to extremely dry (<25cm [<10inches] annual rainfall) settings within a short distance of each other (<40km [25 miles]), topped by alpine deserts on the youngest and highest islands (Giambelluca & Schroeder 1998). All but two of the eight main Hawaiian Islands rise to montane elevations (>1000 m [>3000 ft]). The general patterns of climatic variation found on the largest of the Hawaiian islands are shown diagrammatically below:

Biodiversity Significance

The Hawaiian High Islands Ecoregion is marked by extremely high endemism (e.g., ~90% endemism of native flowering plants; >98% endemism of native terrestrial invertebrates) (Loope 1999). An estimated 15,000 endemic species occur in the ecoregion (Eldredge & Evenhuis 2003). The Hawaiian flora of about 1,200 vascular plant species is disharmonic, that is, lacking many genera and families that typically mark tropical island systems (Sohmer & Gon 1995). Rare and endangered taxa, including endangered plants, forest birds, and land snails comprise >25% of the fauna. Hawaiʻi includes more endangered species than any other state in the U.S. (USFWS 2005). WWF includes the Hawaiian Islands as the site of four of their "Global 200" priority ecoregions (Olson & Dinerstein 1998).

In addition to species, all but a handful of the approximately 150 described terrestrial native natural communities are endemic. Vegetation includes grasslands, shrublands, woodlands,and forests in lowland, submontane, montane, subalpine, and alpine settings (Pratt & Gon 1998). Hawaiʻi supports more Holdridge life form categories than any other ecoregion known (Tosi et al 2001, Ewell 2004). Lists of the natural communities and rare/endangered species of the ecoregion can be found in the appendices.

Biological diversity in the Hawaiian Islands is spread among the main high islands because of island-level endemism. Each island contains species unique to that island. For example, of 1,050 described taxa ofnative flowering plants, there are three found only on Niʻihau, 225 restricted to Kauaʻi, 157 found only on Oʻahu, 40 known only from Molokaʻi, 12 unique toLānaʻi, 96 found only on Maui, 2 reported only from Kahoʻolawe, and 106 known only from Hawaiʻi (Wagner et al 1990).

Because of all of these island-level endemics, fewer than half the flowering plant taxa (409) show multi-island dis-tri-bu-tions. Fewer than 150 can be found on all six of the higher main islands. The situation is even more pro-nounced among invertebrates, which comprise the majority of species-level diversity of the ecoregion, and show remarkable diversification and geo-graphic endemism even within a single island setting.

Human residence and extractive land uses are largely concentrated below 600 m (2000feet) elevation. Land uses include high-density urban, residential, agricultural, grazing, and lands dedicated to military training. Higher elevation areas are more natural, are largely zoned for conservation, and include many areas in protective status such as national parks, natural area reserves, forest reserves, preserves, and refuges. Upland watersheds on most of the main islands are included in informal public-private cooperative management areas called watershed partnerships, managed for maintenance and management of forested watershed. Over 30% of the ecoregion is privately-owned, 29% in state holdings, approximately 8% in federal lands, and the remainder in county and other tenure. These proportions also apply to the biologically intact island interiors, necessitating state, federal, and private participation in comprehensive conservation efforts (Hawaiʻi GAP 2005).

The consequences of past land use practices can be seen on Maui island (figure below). Anthropogenic and alien-dominated regions, shown in pink, dominate the lowlands, while native-dominated ecological systems prevail at higher elevations. Typically there is little or no native vegetation below 600 m (2000 feet) elevation. In mesic settings suitable for grazing, the destruction of forest and replacement by alien grasslands extends to the subalpine zone (e.g., on the upper western flank of East Maui below)."

ESTIMATING SITE RESILIENCE

CHAPTER 2

Section 1: Geophysical Settings

We developed geophysical settings to characterize and classify the Hawaiian study area into distinct geophysical “stages” based on enduring elevation and geologic properties. Our premise is that the characteristics of a geophysical setting represent enduring features on the landscape that influence biotic differences in the flora, fauna, and natural communities due to inherent differences in chemistry, texture, moisture, pH, nutrients, drainage, or erodibility. These differences favor, or select against, different subsets of species under current conditions, and we expect that to continue even as species distributions shift in response to climate. The physical characteristics of land also correlate with human land use patterns because properties such as bedrock type and soil texture contribute to the value and suitability of sites for agriculture, development, or mining. As we determined how to partition the study area into geophysical settings, we considered the dual role that geophysical settings play in our analysis as 1) “coarse filters” for capturing the full range of abiotic conditions that support biodiversity, and 2) a spatial stratification useful for comparing sites with similar physical properties to identify the ones with the most microclimatic variety and intact natural cover.

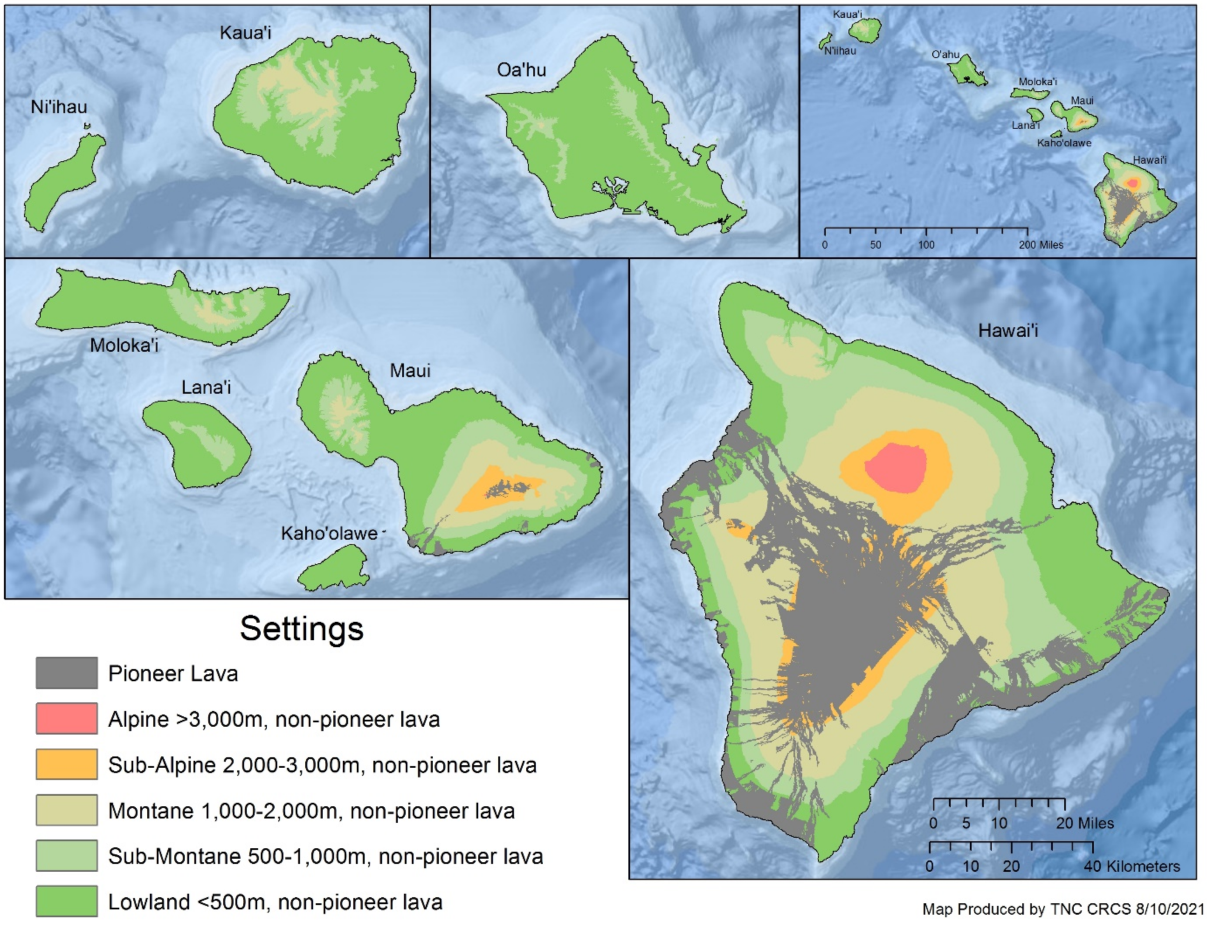
We recognized six geophysical settings in this analysis, five were defined by basalt at different elevation zones, and one was defined by recent lava (Figure 2.1) . The Alpine, Subalpine, Montane and Lowland elevation zone thresholds were taken directly from the Hawaii Ecoregional Plan http://www.hawaiiecoregionplan.info/ecoregion.html, but we divided Lowland zone further into two distinct portions to recognize the unique ecological distinctions between the Sub-Montane and lower Lowland threshold (Sam Gon, personal communication 8/2022). These zones were mapped using a 10-m DEM (USGS, 2020)

Alpine Setting: Above 3,000 m
Subalpine Setting: Between 2000-3000 m
Montane Setting: Between 1,000- 2,000 m
Sub-Montane Setting: Between 500-1,000 m elevation,
Lowland System: Below 500 m

An additional **Pioneer lava setting**, was added as an override on top of the above elevation settings to represent “Young Lava Substrate Areas” as mapped and defined by Price et al. 2012. Young lava substrates impose several well-known influences on vegetation in the Hawaiian Islands. The unweathered nature of most volcanic substrates permits little soil formation and results in a high degree of drainage that retains less moisture than weathered substrates (Kitayama et al. 1995). In addition, younger soils are deficient in nutrients, particularly nitrogen (Crews et al. 1995). The pioneer vegetation associated with young lava substrates is likely inimical to the growth of many plant species that cannot tolerate such conditions; on the other hand, some species such as *Rumex skottsbergii* and *Scaevola kīlaueae* appear to prefer this type of vegetation (Wagner and others, 1990).

The unique properties of the young lava warranted distinct recognition from older basalts. However, we ran it to problems applying our methods for estimating site resilience to this unique setting, as the methods were not designed for fresh or recently cooled lava. Thus, the integrated "resilience" results later in this report are not presented within pioneer lava and further research is needed to map resilience within this setting. This is similar to how we treated glaciers in Alaska.

Figure 2.1: Geophysical Settings of Hawaii



Section 2: Site Resilience

The physical characteristics of a site—its topography, soil characteristics, and the presence of wetlands—can buffer resident species from the direct effects of climate change. Plants and animals experience climate at such local scales that a landscape with topographic variation is experienced as a mix of microclimates: dry to wet, or cool to hot depending on slope position and aspect. Microclimates allow species to find pockets of suitable moisture and temperature even where the average background climate appears unsuitable. Intact sites with little fragmentation and a large variety of microclimates may enable species to persist longer under a changing climate, because individuals and populations can shift their locations locally to take advantage of the microclimate variation.

Sites with little fragmentation and many microclimates are hypothesized to have high **site resilience** because the presence of connected climatic variation allows species to persist and the site to retain diversity and ecological functions longer than sites that are fragmented and flat. In this section, we describe the concepts, methods, and data used to estimate the relative resilience of any given site. The two factors important to the estimate—**landscape diversity** and **local connectedness**—are discussed separately, because the tools for assessing and measuring them are distinctly different.

Site Resilience: Landscape Diversity

Our first site resilience factor - landscape diversity - addresses variation in topography and wetlands as indicator of microclimate variation. Landscape-based climatic variation is substantial, on par with, and often greater than expected climatic changes for a region. Topography redistributes temperature and precipitation so fully that in some landscapes no areas experience the "average" regional climate: basins are wetter, summits are dryer, south-facing slopes are hotter, and north-facing slopes are cooler. The term "microclimatic buffering" (Willis and Bhagwat 2009) has been coined for the situation where climate interacts with topography, moisture and aspect to create suitable climatic combinations for species in areas where coarse-scale climate models suggest unsuitable climate. In effect, microclimates "buffer" the resident species from the direct effects of regional climate change.

By mapping a landscape's relevant variation in topography, aspect and moisture, we can incorporate proxies for microclimate variations into conservation planning. Specifically, the number and variety of topographically-derived microclimates present at a site—its **landscape diversity**—can be used to estimate the capacity of the site to maintain biological diversity over time (Anderson et al. 2014b).

In this section we describe our methods to build a spatial landform dataset at a resolution of 10 m for Hawaii using topography, aspect, elevation, topographically based moisture accumulation, and wetlands. We then describe our method to quantify landscape diversity at a relatively fine scale across the study area, and to estimate the number of species-relevant microclimates in 40 ha circle around every 10-m cell. The calculation of landscape diversity scores for each pixel included integrating the following inputs:

1. Landform Variety: the variety (count) of all landform types derived from topographic position, slope, aspect, and moisture
2. Elevation Range: additional weight where elevation range was greater than expected from the number of landforms
3. Wetland Density: additional weight to larger wetlands or dense wetland areas

Landform

Landforms are natural features of the earth's surface created by topography - collectively the set of landforms comprises a region's terrain. A single landform can be described as a combination of topographic position, aspect, slope, and moisture (e.g., moist north-facing toeslope). The distribution of landforms in a landscape drive stable patterns of temperature and moisture, and correlate with exposure, nutrient availability, and soil depth (Barnes et al.1982, Forman 1995).

The basic landform unit (a.k.a. ecological land unit, land facet, land segment, elementary landform, or relief unit) is the smallest homogeneous division of the land surface at a given scale. Because each unit is characterized by attributes such as elevation, slope, aspect, exposure, moisture, and topographic position, they can be used at a proxy for topographically-based micro climates, and the number and variety in an area can provide an estimate of the number of microclimates available to species.

To map landforms and quantify microclimates, we developed a GIS model that divides and classifies a continuous terrain surface into one of 16 landforms. Our methods are based on those of Fels and Matson (1997), and are described in detail elsewhere (Anderson 1999, Anderson et al. 2012).

We used a 10-m digital elevation model as our terrain input. This DEM was created for Hawaii by mosaicking source 1/3 arc second DEM geoTIFFs downloaded from USGS National Map Downloader https://viewer.nationalmap.gov/basic/#productGroupSearch 3/19/2020. The mosaic result was projected to our Hawaii projection NAD83 projection and resampled to 10-m using bilinear resampling. As a final step before landform generation, we ran a standard 3x3 cell low-pass filter on the 10-m which reduces the significance of anomalous cells and we filled sinks for the further terrain and hydrological modeling.

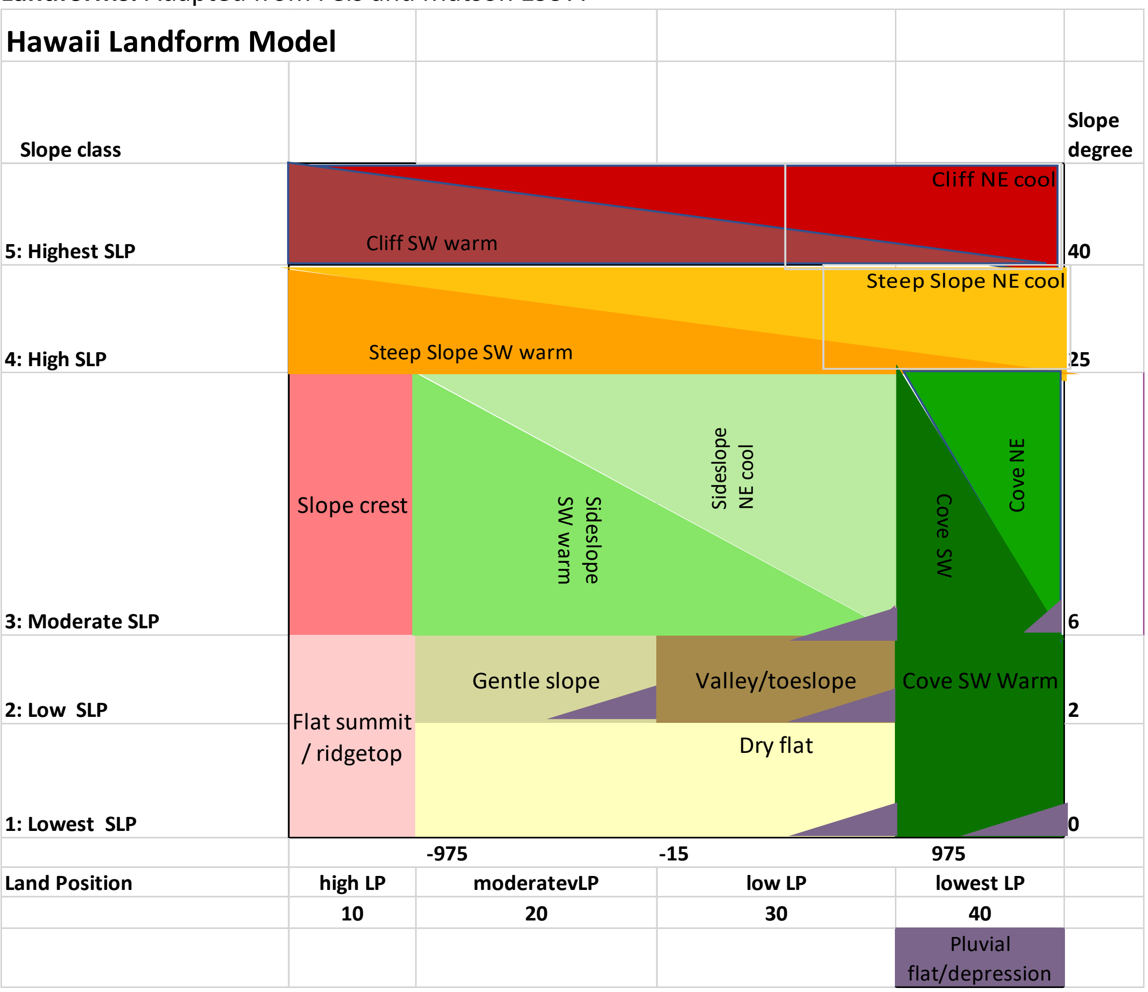
We derived estimates of slope, aspect, land position, and moisture for each 10-m cell in the study area using this statewide DEM. For slope, aspect, and land position, we defined thresholds that allowed us to partition values into different major landform zones that corresponded with recognizable distinctions of landforms in the field (Figure 2.2). The primary divisions in the model were based on relative land position and slope (X and Y axis in Figure 2.2). Some slope classes were then further divided by aspect. Sideslopes and flats were further divided by a moisture index.

Each of these DEM derivatives is described below:

- Topographic Position Index: The Topographic Position Index (TPI) compares the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell. For example, if the model cell was, on average, higher than the surrounding cells, then it was considered closer to the hill top (a more positive position value), and conversely, if the model cell was, on average, lower than the surrounding cells, then it was considered closer to the slope bottom (a more negative position value). In Hawaii, as in our other Lower 48 and Alaska landform work, we evaluated the TPI elevation differences between any cell and the surrounding cells within a search radius of 300m. The final index value was multiplied by 10,000 and intergerized before creating the following classes high to low topographic land position four classes: -976<=, -975 -15 , -14 975, >=976
- Slope: Degree of slope was calculated as the difference in elevation between two neighboring cells, expressed in degrees. The continuous slope was classified into the following groups. Thresholds were consistent with others used in the Lower 48 and Alaska except for the highest two classes which were adjusted to better represent cliff and steep slope patterning in Hawaii with our 10-m DEM: 0-2 2-6, 6-25, 25-40, >40
- Aspect: Aspect was calculated using the GIS Aspect tool which fits a plane to the z-values of a 3 x 3 cell neighborhood around a center cell. The direction the plane faces is the aspect for the center cell. The continuous aspect was divided into general north and south facing aspects as follows: 90-270 = 1, 0 90= 2 & 270-360 = 2
- Moisture index: We calculated a moisture index following a topographic wetness index formula, also known as the compound topographic index (CTI). This wetness index is a steady state wetness index commonly used to quantify topographic control on hydrologic processes. It uses upstream flow accumulation and slope in the formula *Moisture index = ln [(flow accumulation + 1) / (slope + 1)]*. The resultant index was then smoothed using a 3 cell radius circular focal mean.

We then thresholded the moisture index to map areas in landscape where we would expect significantly higher soil moisture and overland upslope flow to accumulate based on the topography. We sampled the wetness index underneath known wetland vegetation and bog communities from the CAH landcover to determine the mean, standard deviation, and range of wetness index values under these known wetlands. We then selected areas > 0.5 SD above the mean wetness index (>1818) under these known wetlands to represent a likely more wet pluvial accumulation zone. Sideslope and other lower slope and landposition landforms coincident with these areas of high moisture index, were reclassified into “pluvial depression landforms”. Additionally, ephemeral and intermittent classed stream and river areas from the NHD high resolution dataset were added to this category of pluvial accumulation moister areas. These types of streams and rivers often fell on the high wetness index pixels and in some cases the stream flowlines helped connect the high moisture index identified groups of cells. These types of stream channels are also expected to be accumulation areas where water would accumulate and flow and create moist environments at certain times of year when there is adequate precipitation.

Figure 2.2: The Underlying Slope, Land Position and High Moisture Index Model used to Map Landforms. Adapted from Fels and Matson 1997.



Wetlands:
Existing mapped wetlands were added as an additional “wetflat’ landform type. These areas were mapped using current wetland vegetation or native bog communities (value 40 and 41) from the Carbon Assessment of Hawaii Land Cover Map (CAH_LandCover, Jacobi et al. 2017). Although the moist pluvial accumulation areas based on the moisture index provided information on where higher water accumulation was likely, the actual wetland vegetation areas from the most recent landcover provided validation to denote existing wetland vegetation or unique wetland types. These areas might also include groundwater-fed wetlands in areas that would be wet not due to overland flow based on topography (as our moisture index would pick up) but due to underground groundwater processes.

Water: Rivers/streams, and Lakes/ponds
Lastly, the natural extent of freshwater streams, rivers, and lakes were incorporated into the landform dataset as a single “freshwater” class. Sources for water included

1. Water Class from the Carbon Assessment of Hawaii Land Cover Map (Jacobi et al 2017) This water represented natural waterbodies and had already had non-natural small reservoirs and farm storage tanks and ponds removed.
2. National Hydrography Dataset High Resolution Flowlines: https://www.usgs.gov/national-hydrography/nhdplus-high-resolution, Perennial stream and river centerlines were extracted using a query to select "Feature_Ty" = 'STREAM/RIVER' AND "Description" = 'Hydrographic Category|perennial'
3. National Hydrography Dataset High Resolution Area: https://www.usgs.gov/national-hydrography/nhdplus-high-resolution Perennial stream an river wide area polygons were extracted using a query on FTYPES as follows: Stream/River 460, Canal/Ditch 336, Area of Complex Channels 537, Rapids 431, and Inundation Area 403

The final map shows 16 distinct landforms (Figure 2.3 and 2.4).

Figure 2.3: Landform Example: Kauai. Landforms in the vicinity of Puanaioa Point Kauai.

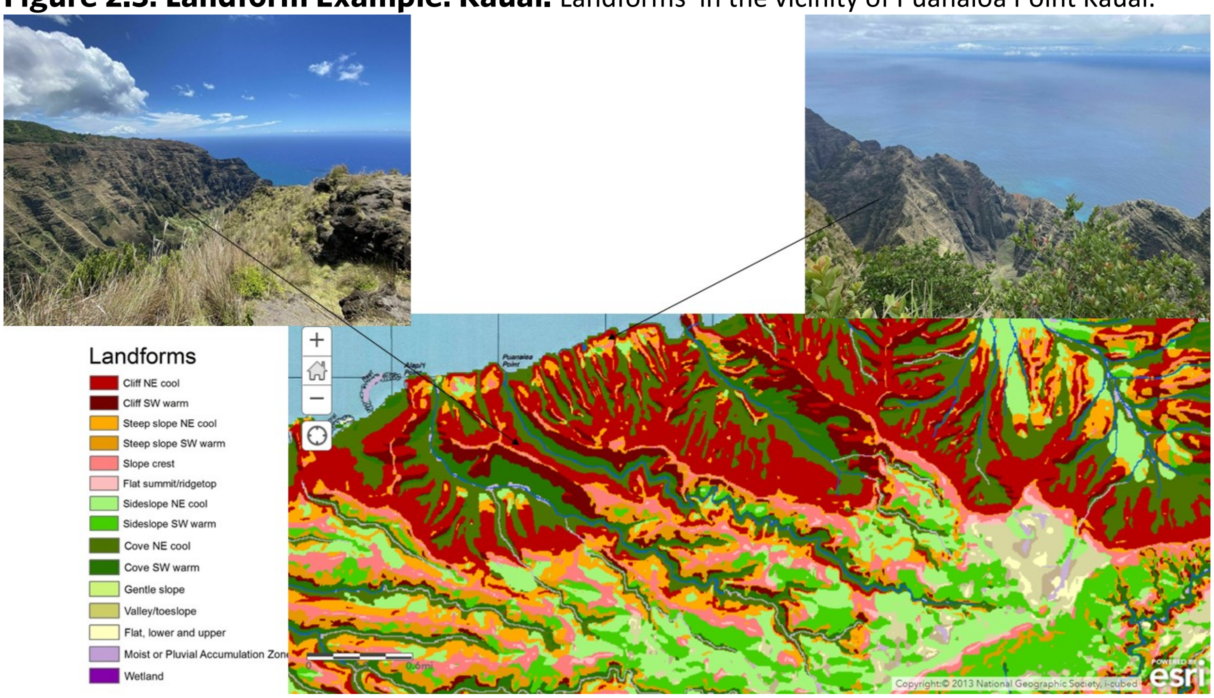
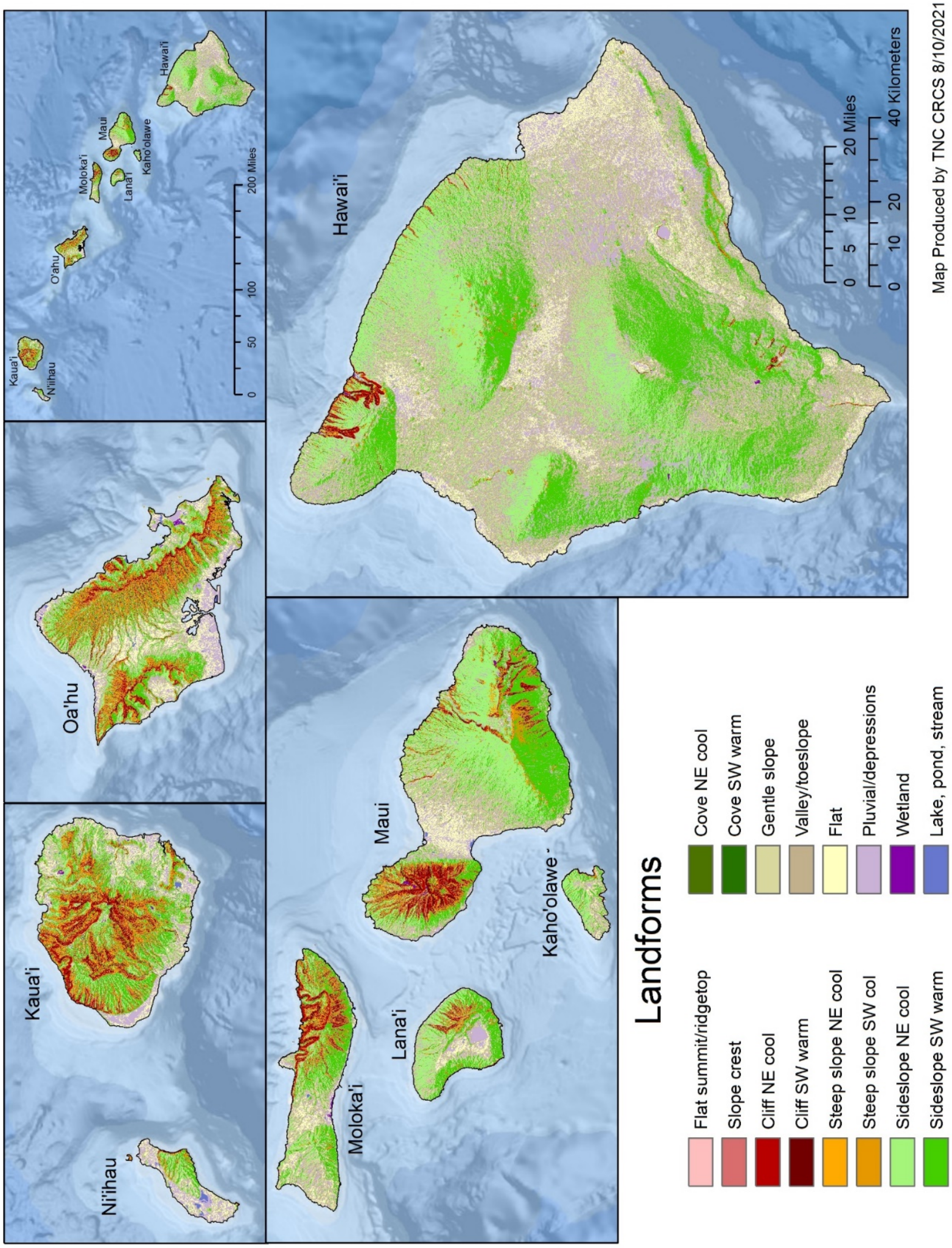


Figure 2.4: Landforms. These landforms are used to characterize the region's topography and to calculate the landform variety metric (10-m cell mapping resolution).

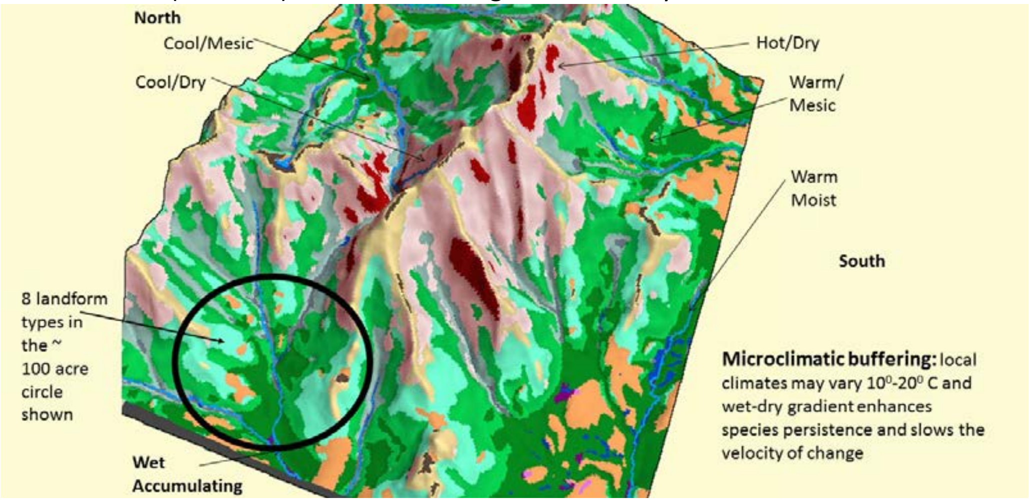


Landform Variety

To identify areas with the highest diversity of microclimates, we calculated the variety of landforms in a 40.4 ha (100-acre) circle surrounding every 10-m cell (Figure 2.5) using a focal variety analysis. This search area corresponds to roughly a 350-m radius around each focal cell and was chosen to conform to our resilience methods used throughout the lower 48 states. We also found this search circle size provided the most differentiation (highest standard deviation) between cell given increasing radii from 50 acre to 200 acres and provided intuitive differentiation in the underlying landform patterning. The size is also a reasonable scale at which population movements could access their local neighborhood.

The landform variety count was then transformed into standardized normalized score (Z score) where the mean is zero and standard deviation is 1 for the analysis area. A standard normal transformation (Z-score) is used throughout this project for combining datasets.

Figure 2.5: Conceptual Model for Landform and Landform Variety. Landforms are showing in different colors in this model. Landform variety is the count of the number of different landforms occurring within a 40ha (100 acre) circle in a moving window analysis.



Wetland Density

Large wetlands or wetland concentration areas play an important role in sustaining site resilience. As the climate changes, persistent wetlands will become increasingly important because they retain soil moisture longer and preserve a mixture of organic and wetland soils. Further, wetland basins tend to have high evapotranspiration rates and play a unique role in moderating the climate and sustaining the resilience of a landscape (Geiger et al. 2003). Protecting wetlands and riparian corridors has been suggested as one of the single best actions in promoting resilience and in sustaining biodiversity (Naiman et al. 1993, Fremier et al. 2015). We expect the current wetlands will continue to be important under variable climates even though the size and wetness of the areas are likely to change. Small, isolated wetlands are often more vulnerable to shrinkage and disappearance than wetlands embedded in a landscape dense with other wetlands. Our wetland density metric was intended to identify and map these dense and larger wetland areas.

To analyze the distribution of current wetlands, we compiled a base dataset of mapped wetlands using current wetland vegetation or native bog communities from the Carbon Assessment of Hawaii Land Cover Map (Jacobi et al. 2017) as discussed above in the landform section. We calculated a wetland density score using two scales, the percentage of wetlands within a 40.4 ha (100-acre) circle and within a 404 ha (1000-acre) circle centered on each input 30-m cell. We excluded open water from the density calculation so that density was relative to the amount of land. We included two scales to provide better discrimination between sites that might look identical at the 100-acre scale and include a larger zone of influence in which wetland microclimates and habitat values would be available to terrestrial ecosystems. To integrate the two scales, we first did a log10 transformation because the source values were non-normal (skewed low) and then created Z scores for each scale (100 acres, 1000 acres) for the region. Areas with a wetland density of zero were assigned a Z score of -3.5 SD (lowest number). We combined the Z standardized values from both search distances using the formula below, giving twice the weight to values from the smaller (100-acre) circle, the same scale used in landform variety.

*Wetland Density = (2*100-acre wetland density + 1000-acre wetland density) / 3.*

Elevation Range

Our goal in the elevation range analysis was to identify areas had more elevation range than would be expected by their number of landforms. We were particularly interested in identifying high elevation range options within a small distance which has been shown to offer climate relief to many species (Chen et al. 2017).

Using a 10-m Digital Elevation Model, we calculated the total elevation range in a 40 ha (100-acre) circle surrounding each cell using a focal range analysis (the same search area as for the landform variety analysis). We converted the output using a log10 transformation given the input values were non-normal and then converted the results to Z-score for the region to identify areas of relatively higher or lower elevation range.

Landscape Diversity: Integrating Landform Variety, Wetland Density, and Elevation

In the landscape diversity metric, we created an integrated metric based on the landform variety score that was increased if wetland density or elevation range were above average and significantly higher than the landform variety score. To do this we created two additional indices:

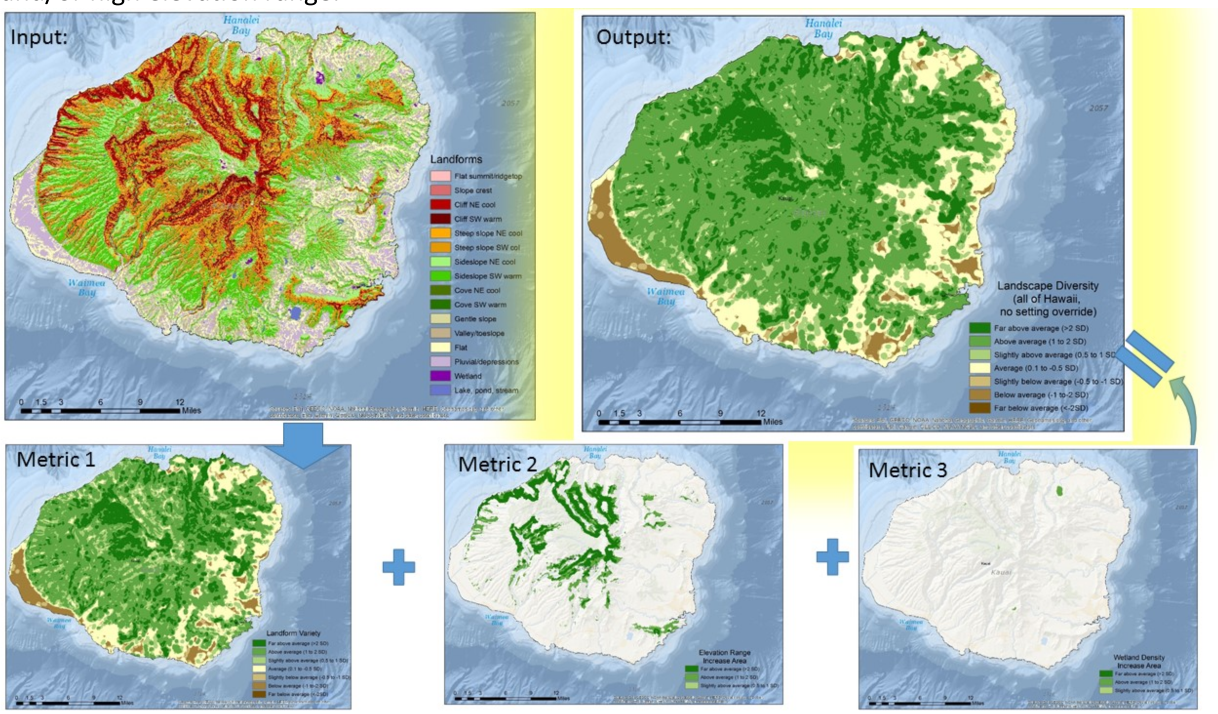
<u>Wetland Density Boost Area</u>

We subtracted the landform variety score from the wetland density score such that a positive difference indicated the wetland density was greater than the landform variety relative to their respective means. We then identified areas where wetland density was both 1) above the mean (>0.5 SD) and 2) the difference between wetland density and landform variety was also above the mean (>0.5 SD). To these areas, we gave a boost (0.5 – 2.0 SD) to the landscape diversity score by proportionally rescaling their original Z scores from a range of 0.5-3.5 to a range or 0.5 – 3.0 and adding them to the landform variety score (Figure 3.6).

Elevation Range Boost Area
We subtracted the landform variety Z score from the elevation range Z score such that a positive difference indicated the elevation range was greater than the landform variety relative to their respective means. We then identified areas where the elevation was both 1) above the mean (>0.5 SD) and 2) the difference between the elevation and landform variety score was also above the mean (>0.5 SD) To these areas, we gave a slight boost (0.25 – 1.0 SD) to the landscape diversity score by proportionally recalling their original Z scores from a range of 0.5-3.5 SD to a range of 2.5-1.0 SD and adding them to the landform variety score (Figure 2.6).

Final Landscape Diversity Score
To create our integrated Landscape Diversity Score, the landform variety Z score was increased if cells were identified by any of the boosting criteria for elevation range or wetland density. The magnitude of the boost varied depending on the cell characteristics described above. In summary, the boosts varied between 1) Elevation Range boost: 0.25-1 SD and 2) Wetland Density boost: 0.5-2 SD and the output base Landscape Diversity score was equal to landform variety score plus the sum of the boosts (Figure 3.13). This was then divided by the standard deviation of the analysis area to appropriately spread out the distribution and approximate standard normal units.

Figure 2.6: Combining Landform Variety, High Elevation Range, and/or High Wetland Density. Base landform variety scores were increased in areas of high wetland density and/or high elevation range.



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Landscape Diversity Score with Setting Override

The base statewide Landscape Diversity map provided a measure for the entire study area irrespective of geophysical settings, but this project aimed to ensure we ultimately have a view of resilience that identify within each settings those areas that have relatively more landscape diversity compared to similar habitats within the same geophysical setting.

To ensure adequate distribution of scores, we stratified the statewide landscape diversity map by geophysical setting to create a "Z" score within each setting (Figure 2.7). This identified those areas within each setting that were relatively higher or lower scoring for landscape diversity. To our base statewide landscape diversity score, we then allowed an "override" to replace the statewide based score if the landscape diversity score was extremely high (>1 SD above average) in the setting. By including these stratifications, we ensured that subsequent resilience scores, which incorporate this landscape diversity score, are representing the areas of highest landscape diversity within each of the settings.

Estimates of landscape diversity within the relatively fresh Pioneer Lava setting appeared insufficient to capture the complexity and unique properties of species establishment in this setting. The Pioneer Lava settings is shown as an overlay on final maps to show its distribution, but further work will be necessary to represent landscape diversity and resilience in this unique setting (Figure 2.8).

Figure 2.7: Combining Stratifications and Overrides. Base landscape diversity was stratified setting and then the statewide base landscape diversity was overridden with the highest scoring areas from each setting to replace with the higher values if those areas were higher than the original ecoregional score.

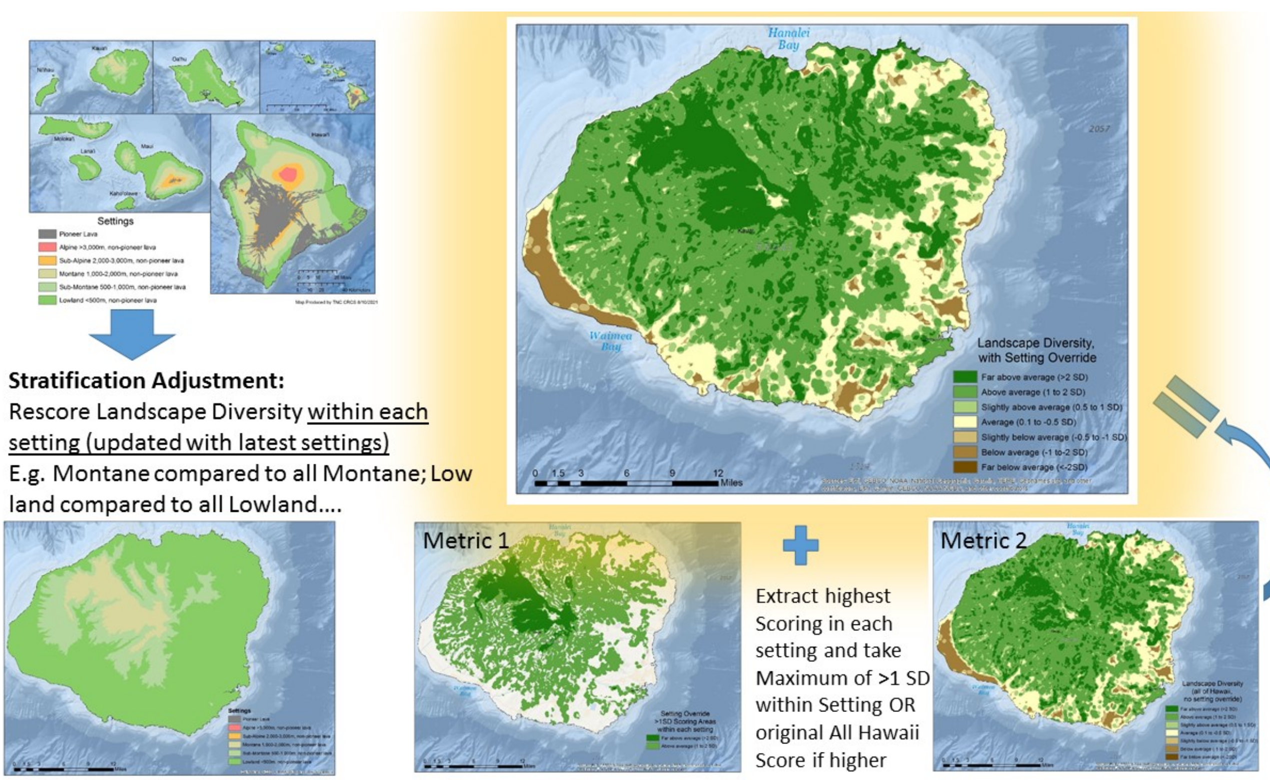
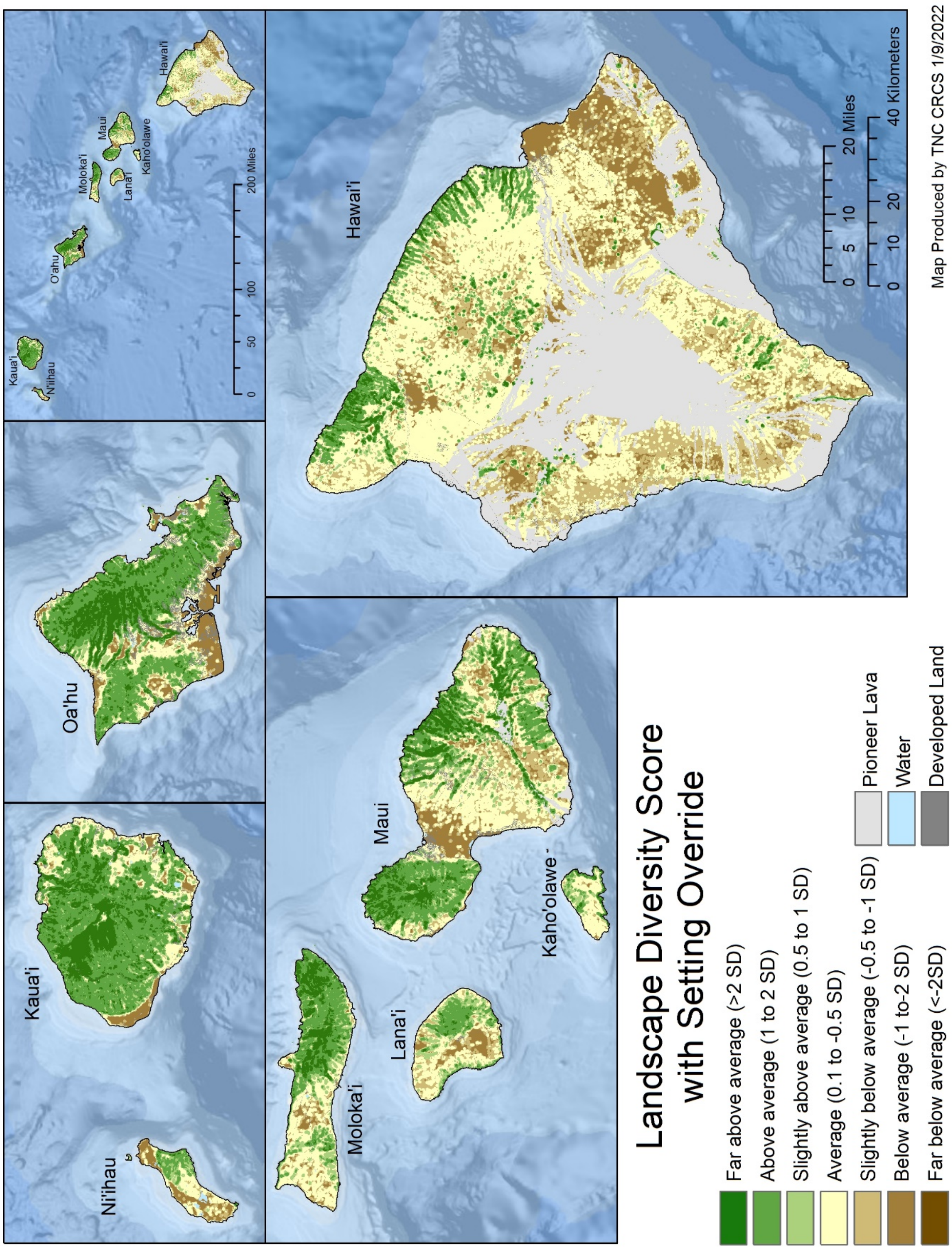


Figure 2.8: Landscape Diversity Score with Setting Override. Landscape diversity combined values of landform variety, elevation range, and wetland density influences. Values are relative within the state of Hawaii, with overrides to include the highest scoring areas within each setting.



Site Resilience: Local Connectedness

Mapping and Scoring Local Connectedness

We mapped local connectedness using a resistant kernel model developed by Brad Compton of the University of Massachusetts (Compton et al. 2007). The first step in running the model was to convert the 30-m landcover and roads data in to a “resistance” grid by coding each land cover class with the resistant weights described above). Resistance weights are assigned by how easy or hard it is for species to move across the surface or pass through a barrier.

Resistance Grid

The resistance grid estimates resistance to species movement due to anthropogenic or natural barriers on the landscape. To create it, we combined and integrated several datasets representing land cover, land use, roads, and development. Our primary data source was the 30-m Carbon Assessment of Hawaii Land Cover Map (Jacobi et al. 2017). We used the Major Land use Classification to classify natural lands, not vegetated, agriculture, and developed lands. This dataset was more recent and accurate then the NLCD we had used in other regions. We upgraded the basic land cover data to improve its performance as resistance grids. The upgrades included improved mapping of:

1) Habitat Status
2) Detailed Roads
3) Building footprints
4) Pioneer Lava
5) Heavy modification of Ni’ihau and Kaho’olawe

Habitat Status:

The natural lands of Hawaii were further classified by their habitat status using the 30 meter Carbon Assessment of Hawaii Habitat Status dataset (Jacobi et al. 2017). This layer depicts the status, or degree of disturbance, to plant communities on the main Hawaiian Islands. There are four categories in this dataset: 1) Bare or <5% Vegetation, 2) Heavily Disturbed, 3) Native / Alien Mix, or 4) Native Dominated. In our model, greater disturbance equaled higher resistance.

Detailed Roads:

Traffic, road width, and road type (paved/dirt) all effect connectivity for species, but our landcover map (Jacobi et al. 2017) did not different road types. All roads are classified as developed. To provide more detail on road class, we removed the roads from the landcover map and replaced them with roads from each county in Hawaii. The developed class in the Landcover map was shrunk by one pixel to remove linear road pixels but not the larger developed areas. Values for these cells were replaced with the majority value of the surrounding pixels. Next, the county roads were burned in on top of the landcover map providing more detail on road class. Each county had its own road dataset with its own schema available from the Hawaii Statewide GIS program. The schemas were harmonized to create one common weighting scheme for the roads (Table 2.1).

Building Footprints:

Landcover datasets often miss or misclassified very low-density residential areas in rural, agricultural, and natural western landscapes. Fortunately, Microsoft has just released a building footprint dataset (Microsoft 2019) that accurately maps all the individual building footprints for the United States based on a sophisticated method employing deep learning, computer vision and artificial intelligence. We downloaded the Hawaii data, converted it from GEOJSON format to ESRI shapefile, and then converted the polygon dataset to a 30-m grid. Any grid cell that contained a building was considered developed.

Table 2.1: County harmonization of road weighting for the resistance grid.

County	*Description*	*Resistance*
Hawaii or Honolulu	A31 - Secondary and connecting road, State and county highways, unseparated	20
Hawaii or Honolulu	A35 - Secondary and connecting road, State and county highways, separated	20
Hawaii or Honolulu	A41 - Local, neighborhood, and rural road, city street,	10
Hawaii or Honolulu	A45 - Local, neighborhood, and rural road, city street,	10
Hawaii or Honolulu	A51 - Vehicular trail, road passable only by 4WD vehicle,	3
Hawaii or Honolulu	IMPS - Houses located along path or trail that an automobile cannot travel on.	2
Hawaii or Honolulu	Q01 - Easements and driveways.	5
Hawaii or Honolulu	Q02 - Private road parcels.	5
Hawaii or Honolulu	Q03 - Compound roads (e.g., within a school compound).	5
Hawaii or Honolulu	Q04 - Alleys	5
Hawaii or Honolulu	Q05 - Agricultural Roads	3
Kauai	Route Type = 3	20
Kauai	Named Roads	10
Kauai	Dirt Road	3
Kauai	Unnamed Road	3
Maui	Major Rural Collector	20
Maui	Major Urban Arterial	20
Maui	Major Urban Arterial	20
Maui	Minor Agricultural Collector	20
Maui	Minor Rural Collector	20
Maui	Minor Urban Collector	20
Maui	Rural Arterial	20
Maui	Local Rural Street	10
Maui	Local Urban Street	10
Maui	Parkway	10
Maui	Service	3

Pioneer Lava:
We treated bare rock and pioneer lava as slightly less connected than natural lands due to its unique properties. Pioneer lava dataset comes from “Young Lava Substrate Areas” as mapped and defined by Price et al. 2012. Areas of pioneer lava were given a higher resistance value with the range of natural lands with native vegetation increasing the score from a 1 to a 1.5.

Heavy modification of Ni'ihau and Kaho'olawe:
Most of islands of Ni'ihau and Kaho'olawe have been heavily modified through grazing and military operations particularly in the flattest parts of the island. We used a topographic roughness calculation to identify areas that were above the average for high topographic roughness for each island. These areas were classified as a Native/Alien mix of habitat and got a lower resistance. The rest of the islands that were more disturbed were classified as heavily disturbed habitat and received a higher resistance.

These modifications were integrated with the landcover map to increase resistance in specific areas (Table 2.2, Figure 2.9)

Table 2.2: Resistance Values for Hawaii

Resistance Value	Landuse description
20	Building footprints, Highways, Secondary Roads
10	Developed
7	Agriculture
5	Driveways, Private Roads
4	Heavily Disturbed Habitat
3	Dirt Roads / Agricultural Roads
1.5	Native/Alien Mix Habitat or Pioneer Lava
1	Natural Lands with Native Vegetation

To run the resistant kernel algorithm, we aggregated the resistance grid to 30 meters by using a mean function to allow for faster computation time. Next, we assigned a maximum distance of 3 km to the model (the default value recommended by the software developer) to represent the distance where the influence on the focal cell is zero. We implemented the resistance kernel model by running focal statistics, neighborhood weighted kernel with center cells having more weight and less weight as you get further from the center to a maximum of three km. The map of all focal cell scores creates a continuous wall-to-wall estimate of local connectedness (Figure 2.10).

Hawaii is a relatively natural landscape; the distribution of cell scores were skewed towards the high local connectedness values. As Z-scores assume a normal distribution we had to use a manual method for transforming the scores into units that could be combined with the landscape diversity scores. To assign class breaks to the local connectedness values we followed a method we developed when mapping Alaska. We started with a interval classification and divided the results into four classes all having a 10 point range. We subdivided the highest category (resistant kernel score 90-100) and assigned it to "average (0 SD)." We assigned the next category (90-95) to "slightly above average (0.5 SD)" – half the range of the equal interval categories. We assigned the next category (95-98) into "above average (1.0 SD) " with a point spread of 3 points, and the final category (98-100) to "far above average (2.0 SD)" with the smallest point spread of 2 points). This weighting scheme allows the most exemplary locally connected areas to be emphasized. In this weighting scheme, areas receiving a local connectedness score of 2.0 SD have very little development within the three-kilometer radius, local connectedness areas scoring 1.0 SD have some development or a mix of native/alien vegetation. Areas that received a score of with 0.5 SD or 0 have native alien mix with more heavily disturbed habitat, agriculture, and roads (Figure 2.11). Areas of mostly agriculture mixed with some native/alien mix score of -0.5 SD. Agricultural areas received scores of -1.0 SD. Areas of highdensity development received scores of -2.0 SD. These scores are comparable to the score weighting in the continental U.S.

Figure 2.9: Resistance Values for Hawaii. Natural lands receive and low resistance score, heavily disturbed habitat and agriculture received medium resistance scores, and developed lands receive high resistance scores.

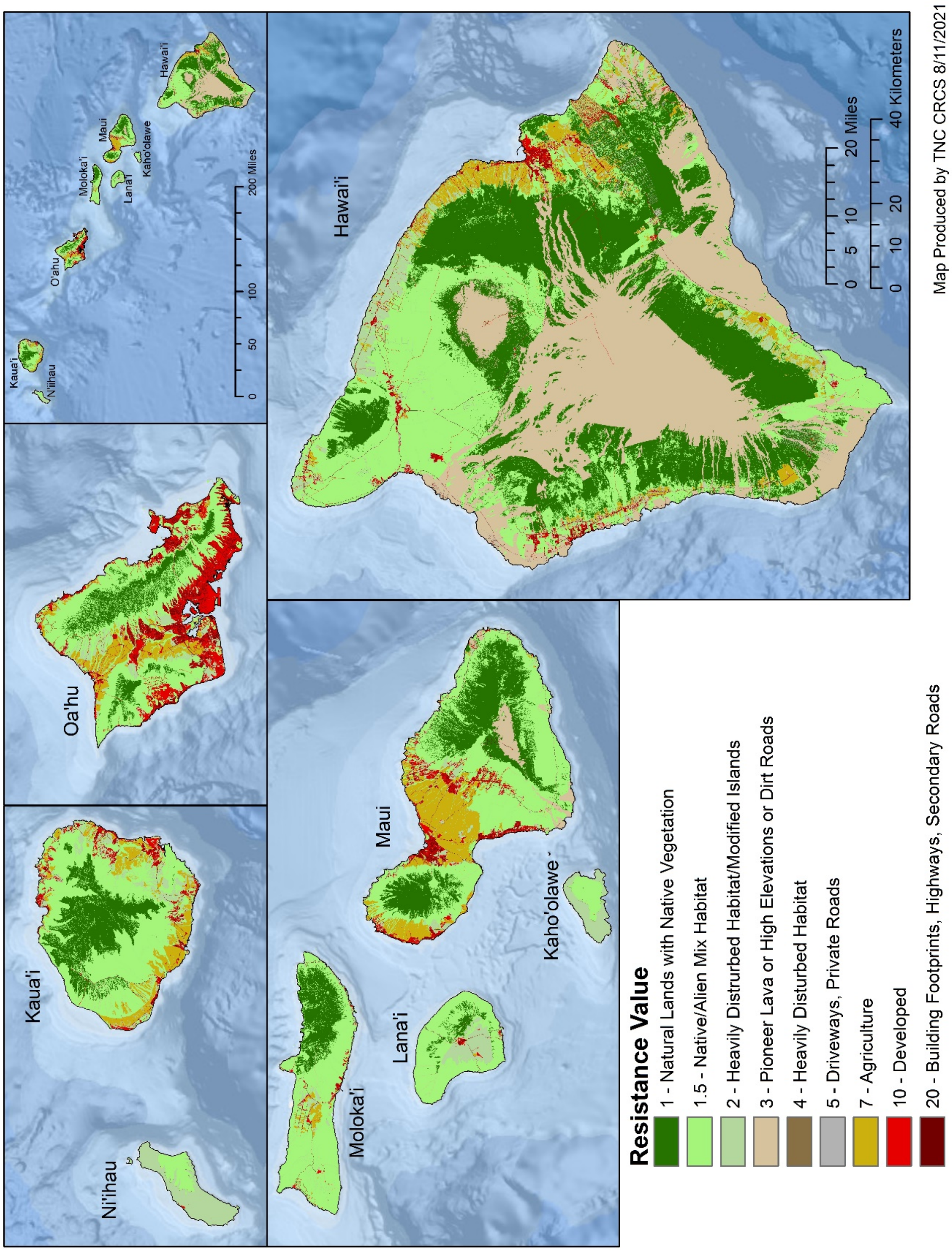


Figure 2.10: Local Connectedness Score for Hawaii. This map estimates the degree of connectedness of a cell with its surroundings within a 3-km radius with a custom ecoregional stratification.

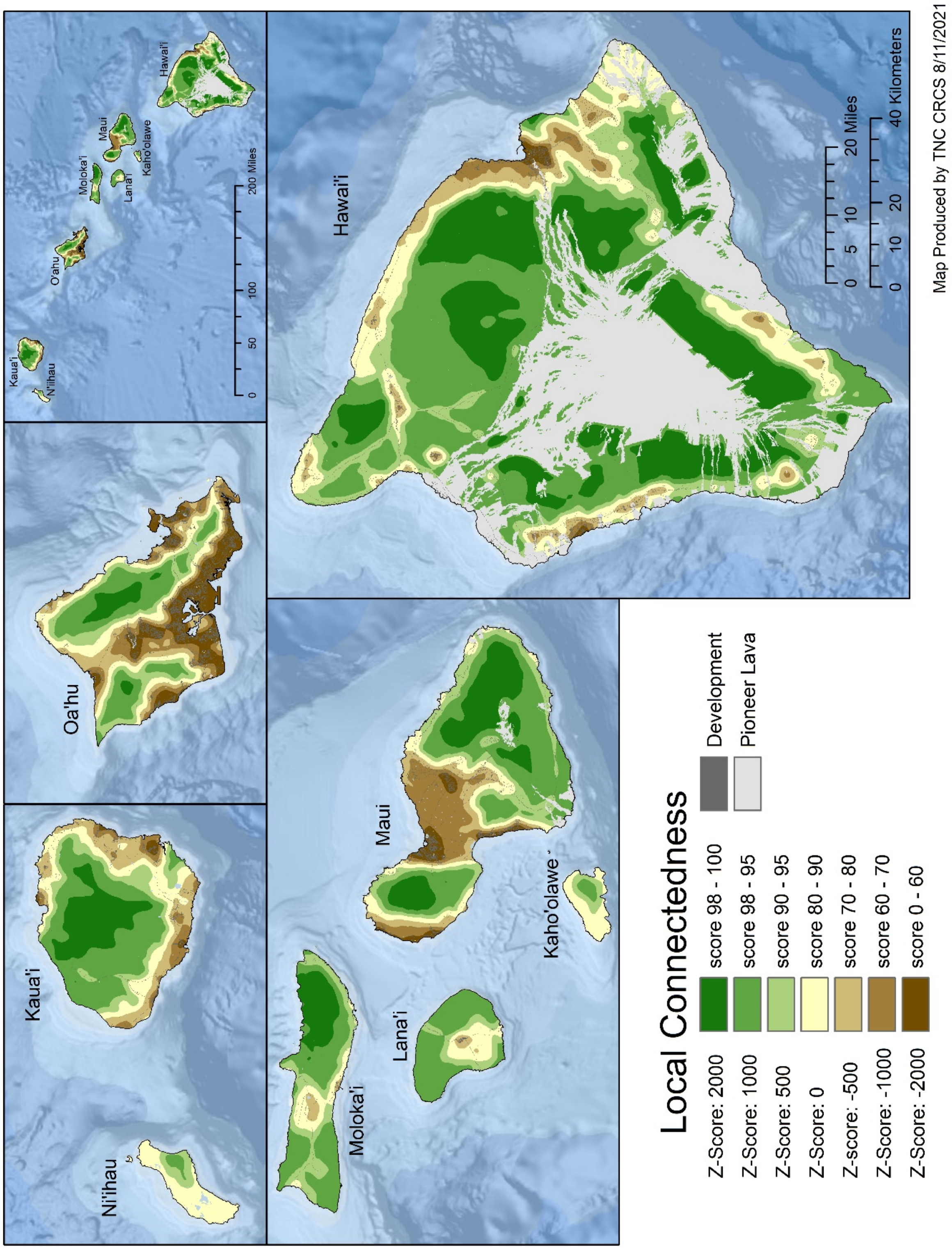


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Figure 2.11: A Gallery of Satellite Images and their Corresponding Local Connectedness Scores. The resistant kernel (RK) classes are based on a roughly circular 3km radius site positioned at the center of each image (not shown).

Far Above Average Local Connectedness

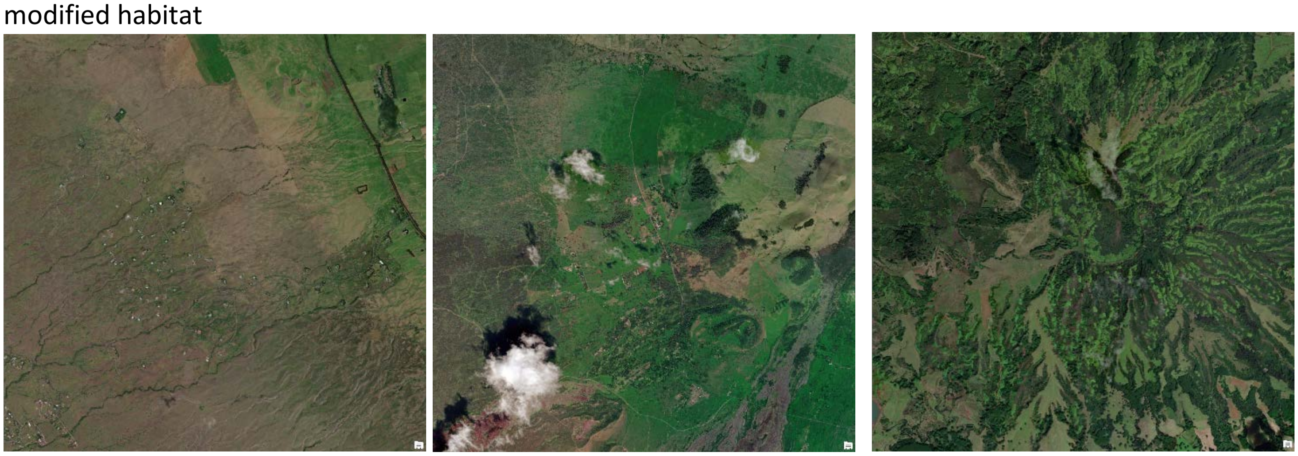
Natural Lands in high condition with no development

Above Average Local Connectedness

Natural lands with a small amount of development (left) or Native/Mix (center, right)

Slightly Above Average Local Connectedness

Native/alien mix with low density development (left, middle) or native/alien mix with some heavily modified habitat



Average Local Connectedness

Native alien mix with more heavily disturbed habitat and agriculture and roads



Slightly Below Average Local Connectedness

Mostly Agriculture Mixed with some native/alien mix



Below Average (Left and Center) and Far Below Average (Right)

Below Average (left and center) - mostly agriculture with some roads. Far Below Average (right) - High Density Development



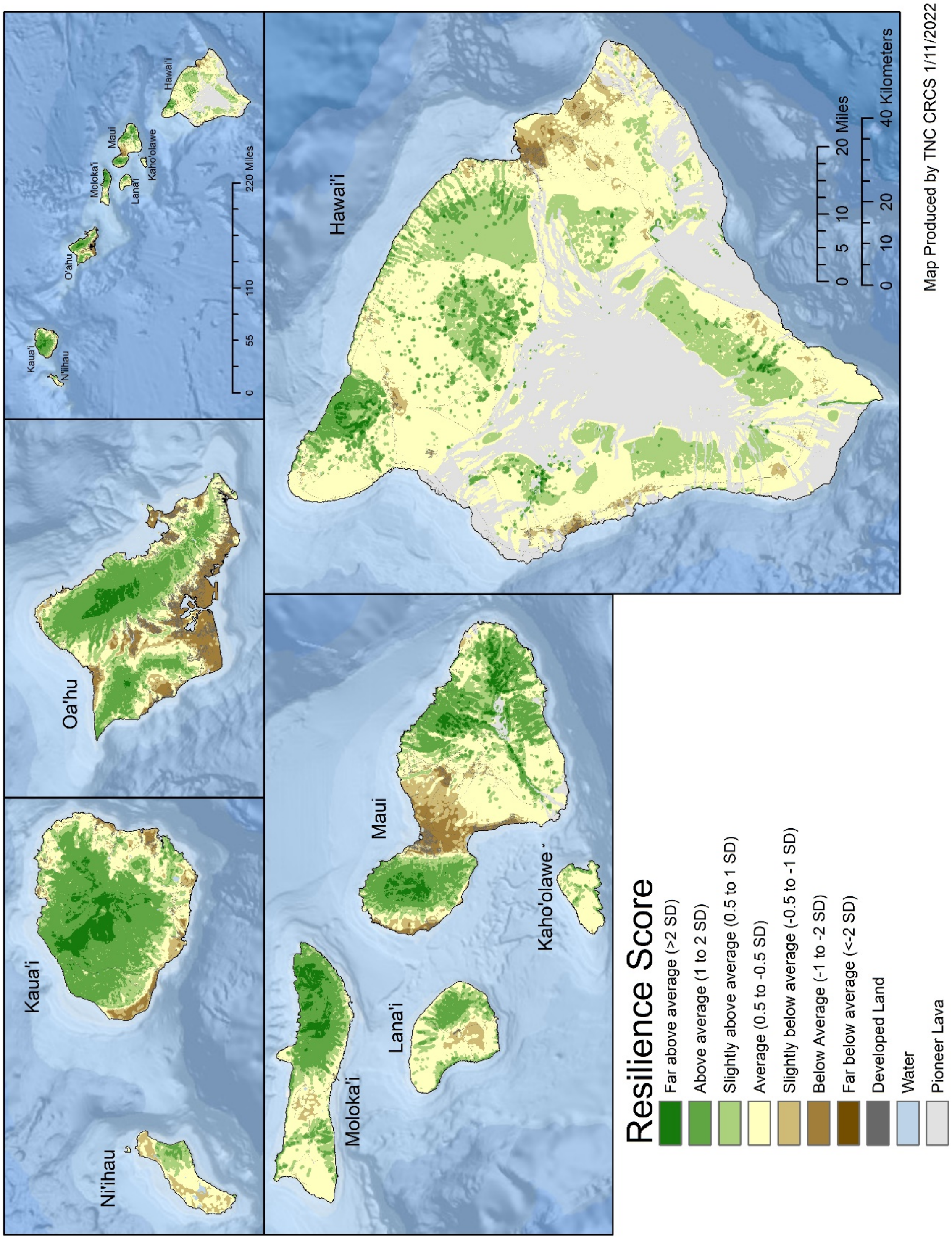
Site Resilience Score: Combining Landscape Diversity and Local Connectedness

We combined the landscape diversity and the local connectivity scores into an integrated site resilience score (Figure 2.12). The resilience score maps the areas where those factors combine to create connected areas with many microclimates (i.e. high resilience). We combined the two factors giving equal weight to the landscape diversity and local connectedness sores:

Site Resilience = (Landscape diversity (z-score) + Local connectedness (z-score)/2

The site resilience score may be used as an estimate of a site's potential to support biodiversity into the future under a variety of climates, but we encourage users to look closely at the individual factors as they reveal interesting and different information about the landscape.

Figure 2.12: Resilience score. This map shows the Resilience Score (landscape diversity + local connectedness) for the hawaii region.



RECOGNIZED BIODIVERSITY AREAS

CHAPTER 3

The central idea of a conserving-the-stage approach to conservation is that rather than trying to protect biodiversity one species at a time, the key is to conserve the geophysical “stages” that create diversity in the first place at local and regional scales (Hunter et al. 1988, Beier & Brost 2010, Lawler et al. 2014). Species ranges are not fixed, and the world has always experienced some measure of climate change. Thus, protecting the full spectrum of physical environments that provide habitat for distinct sets of species offers a way to conserve diversity under both current and future climates (Anderson & Ferree 2010). Toward that end, we performed a separate analysis of resilient sites and identified resilient examples of each distinct geophysical setting but we did not consider the habitats, communities or species populations present at each location. Here we now integrate information on the biota with the physically based resilience map.

To identify a network of sites that could likely sustain biological diversity into the future, we wanted the network of climate resilience sites that contained the maximum amount of thriving biodiversity. To identify areas of high biodiversity value we compiled the results of a few intensive, multi-year studies that mapped the locations of exemplary habitats and rare species populations. For Hawaii, that included the results of the 2010 Hawaii Terrestrial Biodiversity Value Layer and the 2008 TNC Ecoregional Coastal Portfolio).

Hawaii Terrestrial Biodiversity Value Layer (2010)

The Hawaii statewide Terrestrial Biodiversity Value Layer was developed to represent the biodiversity component of the State-Wide Assessment and Resource Strategy (SWARS). The layer was developed with partnership between Jim Jacobi from USGS, Jon Price from UH-Hilo; Ron Cannarella and Emma Yuen from Dept of Fish and Wildlife; Sam Gon, Stephanie Tom, Jason Sumiye, and Theresa Menard from The Nature Conservancy.

Their approach was to incorporate biodiversity richness and biodiversity uniqueness in addition to habitat quality to identify important areas. The biodiversity value layer combined landcover, plant richness and diversity from Hawaii GAP program (HIGAP, Gon 2006), existing vegetation type form LANDFIRE, Bird ranges from Gorresen et. al 2009, USFWS core and supporting waterbird locations (US Fish and Wildlife Service 2011), and TNC’s mapping of previously surveyed coastal vegetation (TNC 2009). Resultant areas were checked against rare species location, forest bird recovery areas, and important seabird areas. Habitat quality, biodiversity richness, and biodiversity uniqueness together identified important areas

Resultant Biodiversity categories were defined & mapped by various meaningful combinations of datasets. Six categories were identified and generally identify important areas for biodiversity conservation across the state. We used the top for categories from the Hawaii Biodiversity Value layer were as core areas of Recognized Biological Value.

Hawaii Terrestrial Biodiversity Value Categories

1. Intact Native Ecosystems – Highest Biodiversity category includes high-quality native-dominated areas where over 100 plant species occur or areas where 4 or more forest birds species are found on Maui, Kauai & Hawaii Island.

2. Intact Native Ecosystems category includes high-quality native-dominated areas where less than 100 plant species are found, including the better native coastal vegetation occurrences. The light green areas also include core wetlands identified by the FWS for the recovery of Hawaiian waterbirds.

3. Threatened Native Ecosystems category includes the best remaining high-quality native-dominated areas that can support 35 or more endemic plants that have lost a lot of their range.

4. Rapidly Degrading Ecosystems category includes medium-quality non-native dominated areas that are in high proximity to native forest edges. On Molokai & Oahu, degraded areas with 3 or more forest bird species are also highlighted in this category.

5. Degraded Ecosystems category includes medium-quality non-native dominated areas that are NOT adjacent to native forests, as well as coastal veg occurrences with fair viability, and supporting wetlands identified by FWS for waterbirds.

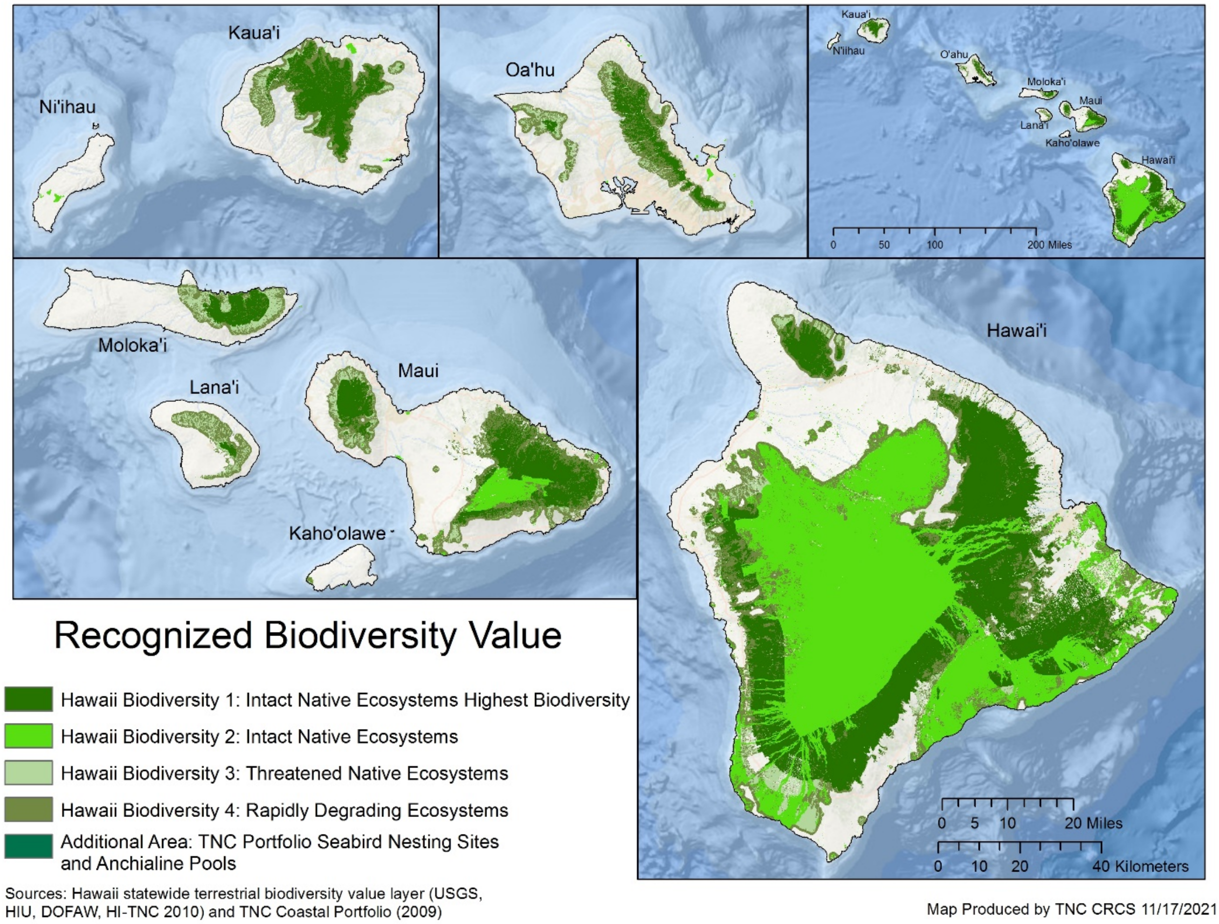
6. Areas where Native Ecosystems No Longer Exist include poor-quality paved over areas or intensive agriculture.

TNC Ecoregional Coastal Portfolio (2009)

The Nature Conservancy implemented a series of biodiversity assessments across each of the 81 terrestrial ecoregions in the U.S. (1998-2008). The goal of each assessment was to identify a portfolio of sites that, if conserved, would collectively protect multiple viable examples of a set of focal conservation targets - species and communities characteristic of, or unique to, each ecoregion. Viability criteria were based on the size, condition, and landscape context of each biodiversity element occurrence (EO), and the results were reviewed by local experts familiar with the species and communities of the ecoregion. The assessments were performed and evaluated by teams of scientists from both TNC and other NGOs or agencies.

The TNC coastal vegetation ecoregional portfolio and other components of the original TNC Terrestrial Ecoregional Plan portfolio had already been incorporated into the Hawaii Terrestrial Biodiversity Summary. However, the TNC portfolio Anchialine pools and portfolio Coastal Seabird Nesting sites were not already specifically included in the Hawaii Terrestrial Biodiversity Summary. To add these additional sites, the viable anchialine pools and coastal seabird nesting sites were buffered by 100 meters and converted to a 100--m resolution grid to match the scale of the Hawaii Biodiversity Summary raster product. These additional areas were then added the top four categories from the Hawaii Biodiversity Summary to map Recognized Biodiversity Areas (Figure 3.1).

Figure 3.1. Recognized Biodiversity Areas. The top four categories from the Hawaii Terrestrial Biodiversity Summary (Jacobi et al. 2010) and the TNC Ecoregional Portfolio Anchialine pools and Coastal Seabird Nesting (TNC 2009) were combined to highlight areas of Recognized Biodiversity Value.



SECURED AREAS

CHAPTER 4

We compiled information on tracts of permanently protected conservation land. The information is part of TNC's "secured land" dataset defined as land that is permanently secured against conversion to development. This definition was developed by an international group of scientists to differentiate "secured land" from the International Union for Conservation of Nature (IUCN) term "protected areas" which refers to land with a formal designation of conservation value (Dudley 2008). The secured lands dataset includes many tracts of land with no formal designation but substantial conservation value, such as reserves held by The Nature Conservancy or "forever wild" easements held by a non-governmental conservation entity. In contrast, the dataset excludes some designated protected areas such as world biosphere preserves, as these areas are not formally protected from development.

To identify secured lands in Hawaii we used two primary sources 1) Hawaii Reserves compiled by HI-TNCFO as of 4/21/2021 and 2) Conservation District Subzones by Office of Planning, State of Hawaii, Revised 2015. We attempted to crosswalk these datasets into a TNC-GAP Status assignment to match our national Secured Areas dataset as compiled for the Lower 48 states and Alaska. In this work we have used a modified version of USFWS' GAP Status (Crist et al. 1998). Our version (TNC GAP) was similar in concept but used criteria that can be applied more easily and includes consideration of:

1) Intent: the degree that owner, or managing entity is focused on maintaining natural diversity.
2) Duration: the owner or managing entity's temporal commitment to maintaining the land.
3) Effective management potential: the apparent capability of a managing entity to implement the intent and duration based on governance, planning, and resource levels. In the US, local, state and federal agencies, conservation NGOs, and land trusts are considered as effective managers.

The TNC GAP system is a land classification system and it does not necessarily describe how protected the contained conservation targets are within a secured area. For example, a species breeding on a secured parcel may be only partially conserved if their conservation calls for securement of multiple breeding areas and enough winter habitat. In this case, meeting the species conservation goal would require a network of secured lands each with the appropriate level of securement.

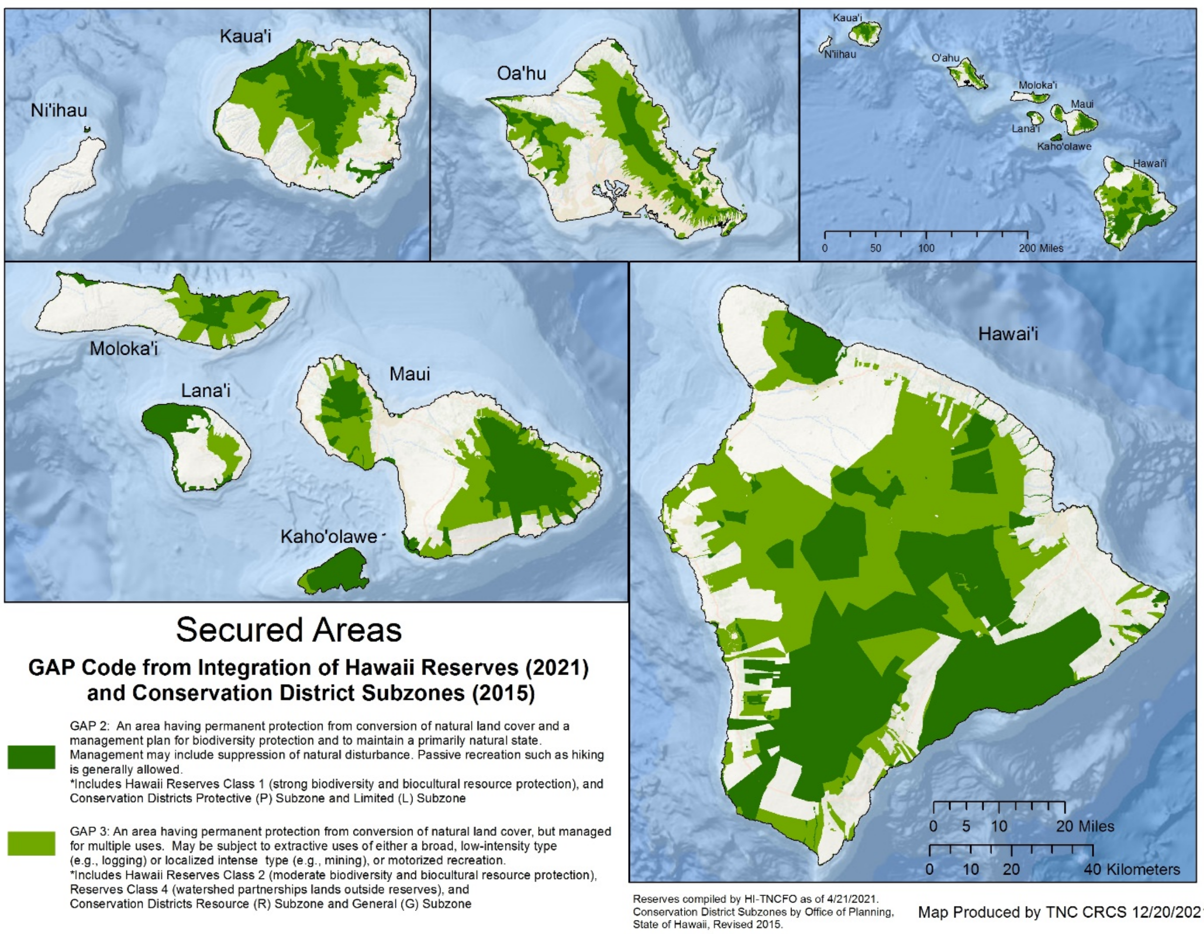
To crosswalk the Hawaii Reserves (2021) and Conservation District (2015) data into general TNC-GAP status categories of conserved for nature (GAP 1-2) or conserved for multiple use (GAP 3) that would be used in our Resilient and Connected Network integration, we did a GIS union to combine the two datasets. We then classified each polygon as follows, using the highest level of protection if/when categories between the Reserves and Conservation Districts disagreed (Figure 4.1).

<u>GAP 1:</u>
Definition: Areas having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events can proceed without interference or are mimicked through management.
Includes: Not used for Hawaii as all natural areas are subject to some management

<u>GAP 2:</u>
Definition: An area having permanent protection from conversion of natural land cover and a management plan for biodiversity protection and to maintain a primarily natural state. Management may include suppression of natural disturbance. Passive recreation such as hiking is generally allowed.
Includes: Hawaii Reserves Class 1 (strong biodiversity and biocultural resource protection), and any areas in Conservation Districts Protective (P) Subzone and Limited (L) Subzone

<u>GAP 3:</u>
Definition: An area having permanent protection from conversion of natural land cover, but managed for multiple uses. May be subject to extractive uses of either a broad, low-intensity type (e.g., logging) or localized intense type (e.g., mining), or motorized recreation.
Includes: Hawaii Reserves Class 2 (moderate biodiversity and biocultural resource protection), Reserves Class 4 (watershed partnerships lands outside reserves), and Conservation Districts Resource (R) Subzone and General (G) Subzone

Figure 4.1: Secured lands. This map shows the secured lands in the study area by GAP status.



LANDSCAPE PERMEABILITY

CHAPTER 5

Circuitscape Model

All modeling of landscape permeability, connectivity and regional flow was done using Circuitscape (McRae & Shah 2009). Circuit modeling recognizes that movement through a landscape is affected by a variety of impediments (resistances) and quantifies the degree to which these impediments will affect movement and the directional outcomes of the compounding effects.

The Circuitscape program calculates the amount of “current” moving directionally across a landscape based on an input grid of cells with values indicating their degree of resistance to species movement. One output of the program, a “current” map, shows the behavior of directional flows, analogous to electric current flowing across a surface with varying levels of resistance. Like water moving across an uneven watershed, the flow of current over the resistance surface results in patterns of high and low concentrations very similar to the streams, gullies, eddies, and braided channels associated with the overland flow of water. The program’s ability to highlight flow concentration areas and pinch-points makes it particularly useful for identifying key linkages for permeability. Flow concentration areas are easily recognized in the Circuitscape output by their high current density.

In the Circuitscape program, the landscape is converted into a graph, with every cell in the landscape represented by a node (or a vertex) in the graph and connections between cells represented as edges in the graph with edge weights based on the average resistance of the two cells being connected (Shah & McRae 2008). The program performs a series of combinatorial and numerical operations to compute resistance-based connectivity metrics, calculating net passage probabilities for random walkers passing through nodes or across edges. Unlike a least cost path approach, Circuitscape incorporates effects of multiple pathways, which can be helpful in identifying critical linkages where alternative pathways do not exist (McRae & Beier 2007). More detail about the model, its parameterization, and potential applications in ecology, evolution, and conservation planning can be found in McRae and Beier (2007) and McRae and Shah (2009).

Anthropogenic Resistance Grid

In a Circuitscape analysis, the current flows across the landscape through a resistance grid, with lower resistance being more permeable and higher resistance less permeable. The base grid we used for anthropogenic resistance was land cover (Jacobi et al. 2017), but in theory resistance can be any factor that impedes movement. In the later climate flow model we use slope and land position as well. When based on land cover, obstructions to species movement are assigned high resistance scores based on the degree to which they impede species population movements.

We used the same anthropogenic resistance grid that was created for local connectedness analysis (see Chapter 2 and Tables 2.1 and 2.2). We made a few modification to the grid with respect to pioneer lava, high elevation areas, and heavily modified lands on the two smallest islands (Kaho'olawe and Ni'ihau). For these areas, the resistance was increased: for pioneer lava, resistance was increased from 1.5 to a 3. For high elevation (>2000 meters) the resistance of barren areas was increase to 3. These two areas are characterized by unique new and uncolonized substrate and can from barriers to directional or long-distance movements. Resistances were decreased on the heavily modified lands on the two smallest islands (from a 4 to a 2) to reflect the fact that on these modified islands, highly modified lands were not that different from the less modified portions of the islands.

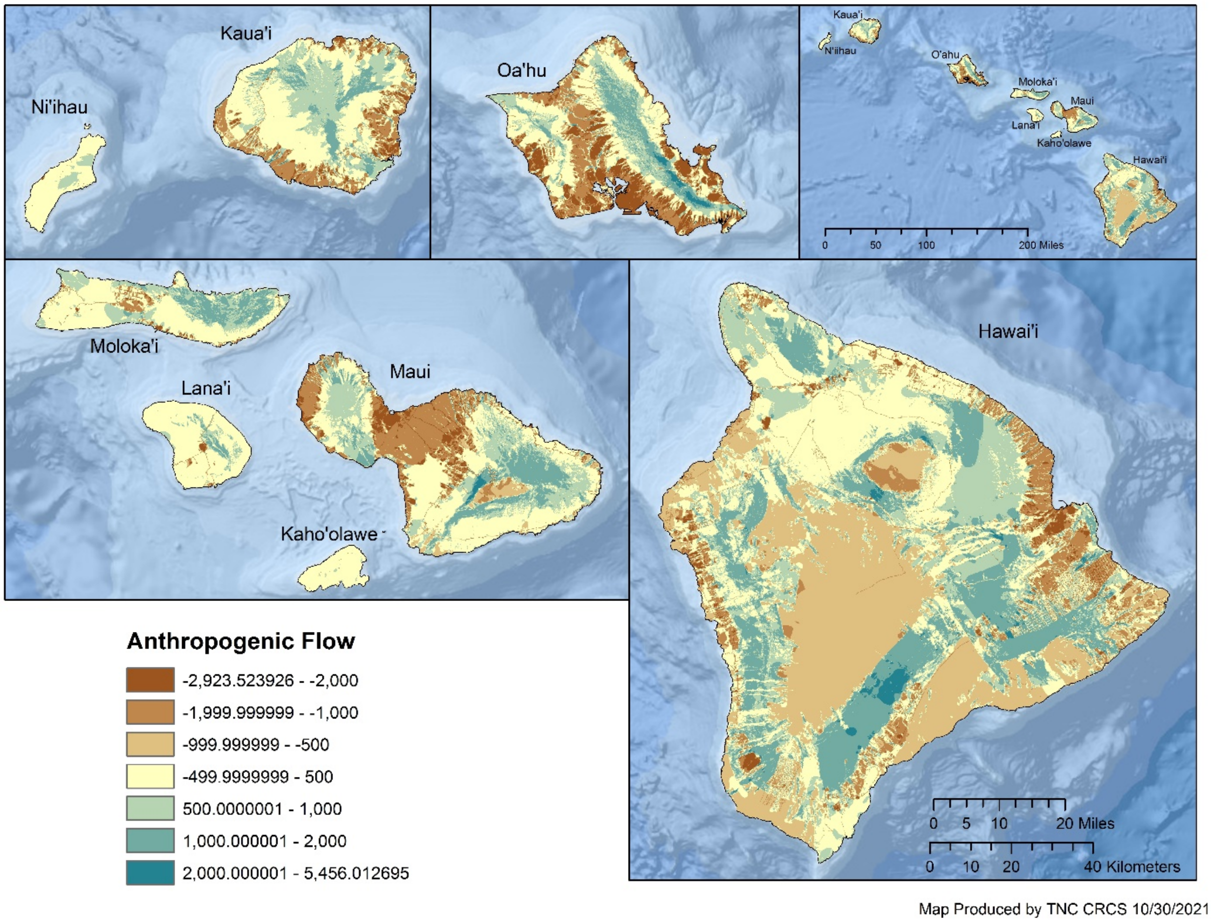
Mapping Regional Flow

Circuitscape was originally designed to measure point-to-point connectivity, calculating resistance-based connectivity metrics from one discrete patch to another. The point-to-point approach has been widely used in conservation planning to measure the connections between two patches of suitable breeding habitat as defined by the precise needs of a species (Beier et al. 2011). However, using a point-to-point approach can limit the utility of assessing connectivity over very large areas, or in evaluating the response of populations to climate change where there are so many habitat patches of interest that assessing connectivity among all possible combinations is prohibitive. Additionally, the point-to-point method is sensitive to the location of the starting points and may produce different results across the same landscape if different starting points are used. To overcome these conceptual and practical limitations, we used a minor adaptation of the Circuitscape model that allows for the "point free" creation of omnidirectional connectivity maps illustrating flow paths across large study areas. Our methods have been developed and refined over several years and were originally described in Anderson et al. (2015) and Pelletier et al. (2014).

Briefly, to obtain a multi-directional and wall-to-wall coverage of the region we ran the model on the Hawaii resistance grid (at 90 meters) in one pass, buffering the ocean using a random grid with the same mean and standard deviation as the resistance grid. One side of the grid was assigned to be "source" and the other side to be "ground." Next, "current" was injected along the entire source side and allowed to flow across the landscape resistance surface towards the ground side. As the current flows it reveals the various flow pathways and highlights where flow gets blocked or concentrated. Because current seeks the path of least resistance from the source cells to any grid cell on the ground side, a run with the west edge as source and the east side as ground will not produce the same current map as a run with the east edge as source and west edge as ground. Runs were thus repeated in each of four directions: east to west, west to east, north to south, south to north, and summed across all directions. The result is a continuous map of omni-directional current flow patterns which we call "regional flow."

The map of wall-to-wall regional flow applied to the anthropogenic resistance grid highlights areas of highest flow in dark blue, areas of moderate flow in medium blue, and areas of blocked or low flow in brown (Figure 5.1).

Figure 5.1: Regional Flow: Results of the wall-to-wall Circuitscape model applied to the anthropogenic resistance grid**.** Brown indicates areas with low permeability. Medium blue indicates areas of moderate flow; often highly natural settings were species movements are diffuse. Dark blue indicates areas of concentrated flow where movements will accumulate or be channeled.



Climate Flow:

This section describes how we modified the regional flow model to specifically highlight connections that provide climate relief. Paleoecological studies show that movement was a near universal response to past changes in climate (Pardi and Smith 2012), but not every directional movement provides equivalent climate relief. Although all parts of the landscape are important in allowing and maintaining population movements, current evidence suggest that areas that offer cooler temperatures or higher moisture are particularly critical in providing local relief from a warming climate. Our goal was to evaluate how these features are arranged on the landscape and whether access to them is limited or prevented by fragmentation, or conversely enhanced by the contours of the topography. We refer to the regional flow analysis informed by features with strong climatic gradients: climate flow. In the previous section we defined "regional flow" as the gradual movement of populations tracking a set of changing conditions over time, and here we define the term "climate flow" to refer to specific directional movements in response to temperature and moisture changes.

A variety of approaches to incorporating climate gradients into connectivity models have been developed. The most straightforward are models that directly connect temperature gradients based on global or national climate data (see McGuire et al. 2016). The climate gradient approach is logical and promising but is currently hindered for our purposes by the coarse scale of the temperature models (typically 1 km or larger). The issue is that these models don't contain the fine-scale topography and microclimate relief that create the local climate environments experienced by most species. Here, we explore climate gradients at a finer scale, and in lieu of fine-scale climate data, we tie the models directly to local landscape features and observed evidence.

In response to climate change, populations are already moving at impressive rates: 3.6 ft. upslope per year and 1.1 miles northward per year in US metrics (Chen et al. 2011). Evidence for contemporary range shifts in response to climate has now been documented for over 1000 species, and can provide insight into the structure and direction of these movements. In response to temperature, the evidence for upslope and northward movements is strong and consistent across many taxa groups and across several continents. In response to moisture and precipitation changes there is rapildy growing evidence for the important role of downslope basins and riparian areas, as well as for eastward movements in some parts of the US.

Following the evidence from recent research, we focused our attention on four well documented responses of species movement to climate change:

Directional
1) Upslope toward higher elevations,
2) Downslope toward moist basins or riparian areas
3) Northward toward cooler latitudes,

Non-directional
4) Locally toward suitable microclimates.

In this section, we model the movement patterns expected from these responses and integrate them into the regional flow map. As with the regional flow map, we incorporate the arrangement and resistance of fragmentation and other human modifications into each model to explore the implications of such modifications on directional movements driven by climate change.

We integrate the directional factors into the flow map as a boost, and not as a fixed determinate of movement. Although the evidence shows that these factors are correlated with population expansions and range shifts, it is also clear that a variety of ecological factors may create variation in a species response to climate such as competitive release, habitat modification, or changes in amounts and patterns of precipitation, snow cover duration, water balance, or seasonality (Groffman et al. 2012). Our decision to give weight to these factors but not to override the other drivers acknowledges that many things might cause a range shift to differ substantially from straightforward poleward or upslope movement largely driven by temperature or moisture (Garcia et al. 2014).

The wall-to-wall Circuitscape approach is well suited to exploring and mapping climate flow because it assumes that every cell in the region is a starting point for some species and the directional movement along elevation gradients could be conceived in terms of resistance, or latitudinal movement as source-ground flow. In the following sections we first look at 1) upslope movement primarily driven by temperature change, and 2) downslope movement primarily driven by moisture changes and 3) northward movement driven by regional temperature gradients. Finally, we integrate these factors into the regional flow model to create a map of climate flow.

Mapping Upslope Movement

To model upslope movement, we created a 30-m continuous landform model based on each cell's relative land position and slope (Chapter 2). We converted this to a resistance grid by first isolating the relative land position value and assigning increased resistance to moving downslope and decreased resistance to moving upslope. Next, we modified the resistance score using the cell's slope value, to reflect the relative degree of effort versus gain in temperature differences (Table 5.1). For example, moving upward along a gentle slope is easy but provides little gain in temperature differences (moderate resistance), moving upward along a moderate slope provides larger gains in temperature differences for moderate effort (low resistance), moving upward along a steep slope is too difficult for most species despite the temperature gains (high resistance). Finally, the resistance on cooler aspects was reduced slightly with respect to warmer aspects. We combined the land position and slope values into one resistance score.

Table 5.1: Resistance scores applied to the landform model. Land position ranks (LP rank) were ordered so they decrease towards higher land positions. Slope (S-rank) were ordered so that they increase at the extremes of no slope (no temperature gain) and steep slopes (too difficult to transverse) and are lowest at moderate values.

Landform	code	Slope	Position	LP rank	S rank	Sum	Weight
Steep slope	3, 4	4 High	any	NA	9	18	9
Cliff	5, 6	5 Highest	any	NA	10	20	10
Flat summit	11	1flat	highest	1	7	8	4
Slope crest	13	3mod	highest	1	1	2	1
Hilltop flat	21	1flat	high	4	7	11	5.5
Gentle slope	22	2gentle	high	4	4	8	4
NE sideslope	23	3mod	high	4	1	5	2
SW sideslope	24	3mod	high	4	1	5	2.5
Dry flat	30	1flat	low	7	7	14	7
Wet flat	31	1flat	low	7	7	14	7
Wetland	32	1 flat	any	4	7	11	5.5
Lower side	33	3mod	low	7	1	8	4
Pluvial/depressions	39	1 flat	Low	7	7	14	7
Slopebottom flat	41	1flat	lowest	10	7	17	8.5
Slopebottom	42	2gentle	lowest	10	4	14	7
N-cove	43	3 mod	lowest	10	1	11	5
S-cove	44	3 mod	lowest	10	1	11	5.5

Although mountainous areas may produce the largest amount of pure elevation change, species also experience temperature relief from slopes relative to their local landscape (e.g., a 10-m slope in a flat landscape may provide more relief to nearby species than a 10-m slope in an already mountainous landscape). To ensure that the model was upslope resistance grid was scaled to both local relief and larger regional relief we calculated both a regional resistance score and a local neighborhood resistance score around each cell and then integrated them.

To estimate regional relief, we calculated the absolute amount of upslope resistance in a 3 km focal area around each cell and converted it to a Z-score using the mean and standard deviation for the whole region. To estimate local relief, we used the same focal statistic algorithm to calculate the mean and standard deviations of upslope resistance for a 3 km radius around each cell and converted the flow to a Z score using only these local means and deviations. The regional and neighborhood resistance Z scores were combined by adding the two grids. We were aiming to give them equal weight, highlighting areas of both absolute upslope flow and neighborhood upslope flow, but the distributions of the two datasets were very different such that the local neighborhood resistance score overwhelmed the regional score. To correct for this, we gave twice the weight to the regional resistance grid. The results provide a single upslope resistance grid that was a weighted combination of regional and local resistance.

To incorporate anthropogenic resistance, we combined the upslope resistance grid with the anthropogenic resistance grid weighting the scores so that the final resistance score of each cell was 50% from the upslope resistance value and 50% from the anthropogenic resistance value. In Circuitscape, we ran current through the combined upslope/anthropogenic resistance grid in all directions (as described previously for the regional flow model) to create an output of upslope current flow incorporating anthropogenic resistance.

The upslope model highlights areas with high potential for upslope range shifts are arranged locally and across the region (Figure 25). The realistic effect of the local scaling is to create a much more distributed picture of where upslope movements may be available to species for local climate relief. This takes the emphasis off the mountains and highlights a wide range of moderate slopes that might play a large role in providing local climate relief.

Mapping Downslope Movement

To model downslope movement, we first identified areas that were down-gradient and lower in elevation than the surrounding landscape. We did this by creating a continuous 30-m dataset that assigned a relative elevation value to every cell by comparing its elevation to its neighbors within a 3 km neighborhood (the same radius used calculate upslope local flow and to calculate local connectedness in the resilience analysis). We used a focal statistic to calculate the mean and standard deviations of the elevations within a 3 km radius, and then calculated a Z-score for each cell based on the neighborhood mean and standard deviation. Values below the mean were lower than their neighborhood and values higher than the mean were higher in elevation than their neighborhood, and these values became the resistance values.

We used the Z-Scored relative elevation surface as a resistance grid in Circuitscape to force current to flow more easily into and throughout the downslope areas as they had less resistance. To give additional benefit to flow in moist areas, we integrated the landform model (described earlier in this section) into the resistance grid and further lowered the Z score within moister landforms. Areas of coves, pluvial moist flats, and wet flats were extracted from the landform dataset and their Z-Score was lowered. Coves were lowered to one quarter -0.25 standard deviations below average, pluvial landforms were lowered to one half -0.5 standard deviations below average, and wetlands were lowered to -1.0 standard deviations below average if the elevation-based Z score was not already less than theses scores. This lessened the resistance slightly in moist and wet areas allowing current to flow more easily. This moisture enhanced Z-scored resistance surface was used as the downslope resistance grid in further Circuitscape flow modeling.

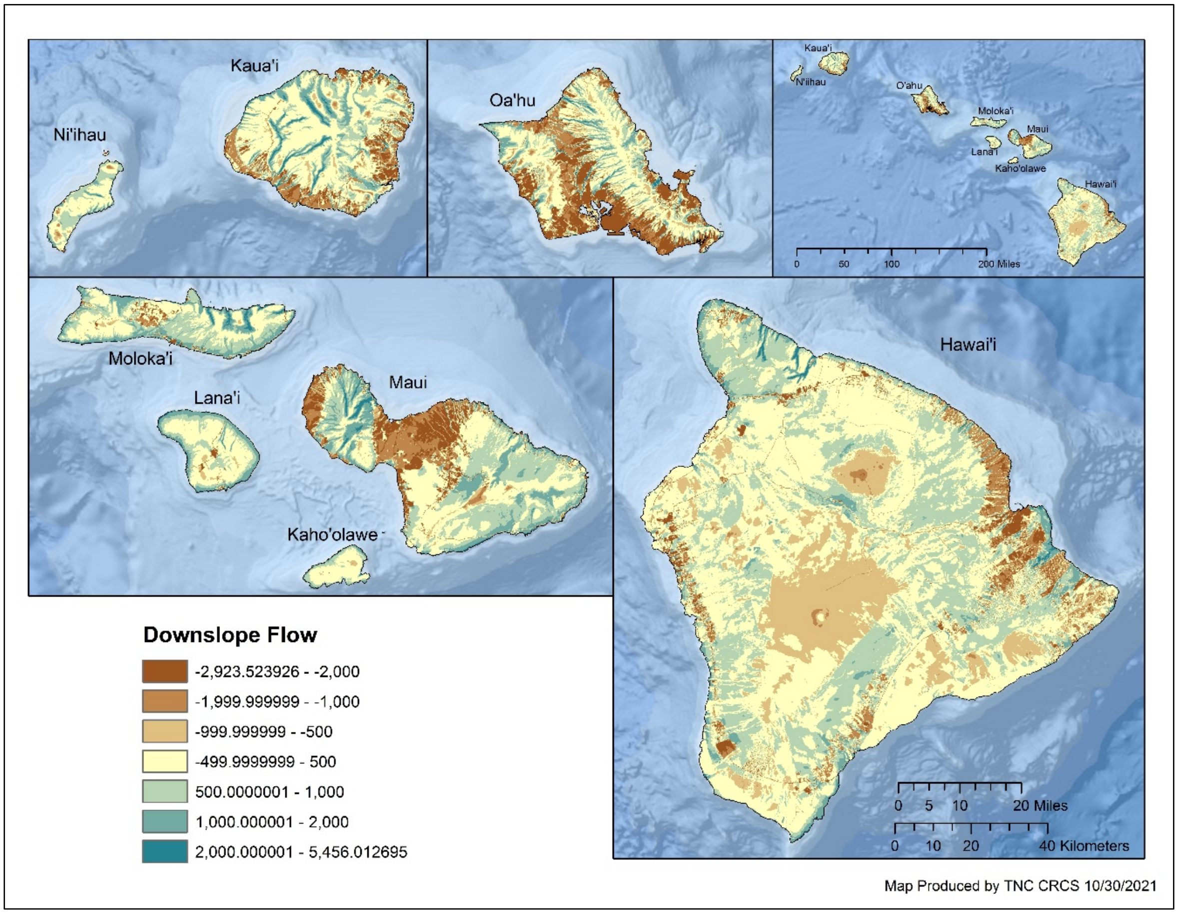
We tested the model in Circuitscape by running current through it in all directions (as described for the regional flow model) to create an output of “current” flow based on the downslope and moisture-enhanced resistance surface. The output tracked downslope moisture patterns at a fine scale, but at this point did not account for any anthropogenic modifications of the landscape.

To create an integrated final downslope model that included human uses, we combined the downslope, moisture-enhanced resistance grid with the anthropogenic resistance grid to create a resistance surface that favored moving downslope but was sensitive to anthropogenic barriers. This was achieved with a 50/50 weighting of downslope resistance and anthropogenic resistance.

The Circuitscape analysis on the resultant resistance grid shows how the areas with high potential for downslope and moist range shifts are arranged locally and across the region, and how they intersect with anthropogenic resistance (Figure 5.2).

The downslope model has very high flow accumulations in the valleys and streambeds, but we wanted to limit the downslope flow to only areas of high flow accumulation. To accomplish this, we only included downslope flow when the score was above 1 SD.

Figure 5.2: Downslope model. This map shows the results of the moisture-enhanced downslope model with anthropogenic resistance weighted at 50% and downslope flow weighted at 50%.



Climate Flow Model: Integration of Upslope and Downslope

For our final model, we weighted the regional flow model with the upslope and downslope models to simulate species populations could flow through the natural landscape finding climate refuge both by moving up or down slopes. Note: unlike other study regions in the US, Hawaii is close to the equator, so northward flow has no effect on cooler temperatures. It was not included in our climate flow model.

When combining the factors, a challenge was how to weight the influence of each factor in a way that most closely approximates the real world. We wanted to keep the emphasis on the areas that are important for regional flow, while boosting slightly the areas that channel slope-based movements. We accomplished this by using the anthropogenic regional flow map as our based dataset and boosted the score of cells if they were important for upslope or downslope movement. For each of the two factors we took the areas that were above-average with respect to their factor.

We overlaid each factor on the regional flow map and replaced the cell score if the cell score for the factor was higher (Figure 5.3 and 5.4). For example, a cell score of 1.2 for Upslope would replace a Anthropogenic Regional Flow score of 1.0, giving a slight bump-up to the cell reflecting its slope. If both factors had scores higher than the northward regional flow score we replaced the latter with the highest score. This had the effect of raising the scores in areas with above-average current flow for upslope, downslope movement but still retaining the northward regional flow score, and thus not penalizing areas for not having slopes.

Figure 5.3: Climate Flow showing Upslope and Downslope Components. The results of a Circuitscape analysis applied to the regional flow grid and weighted for above-average upslope flow (periwinkle blue), or downslope flow (bright blue).

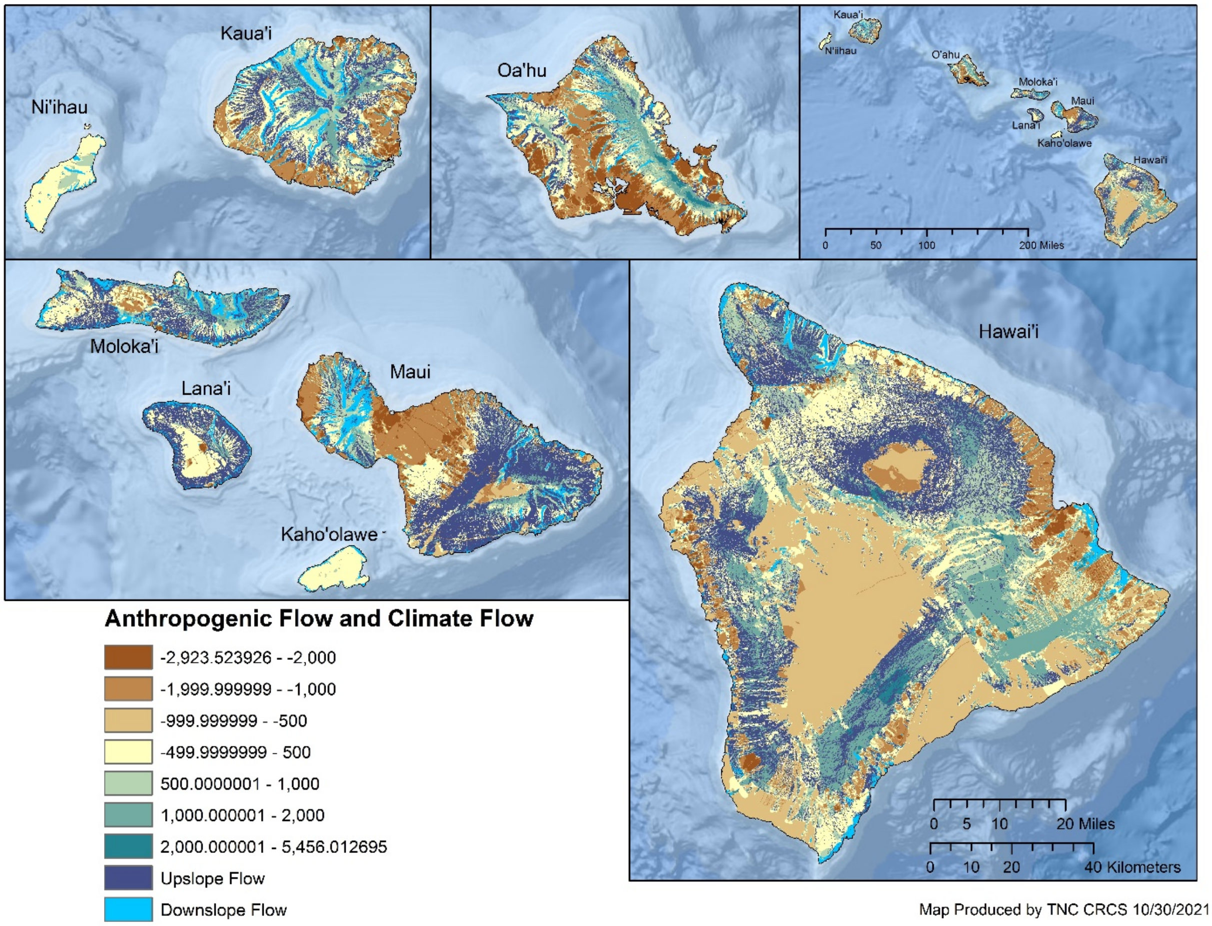
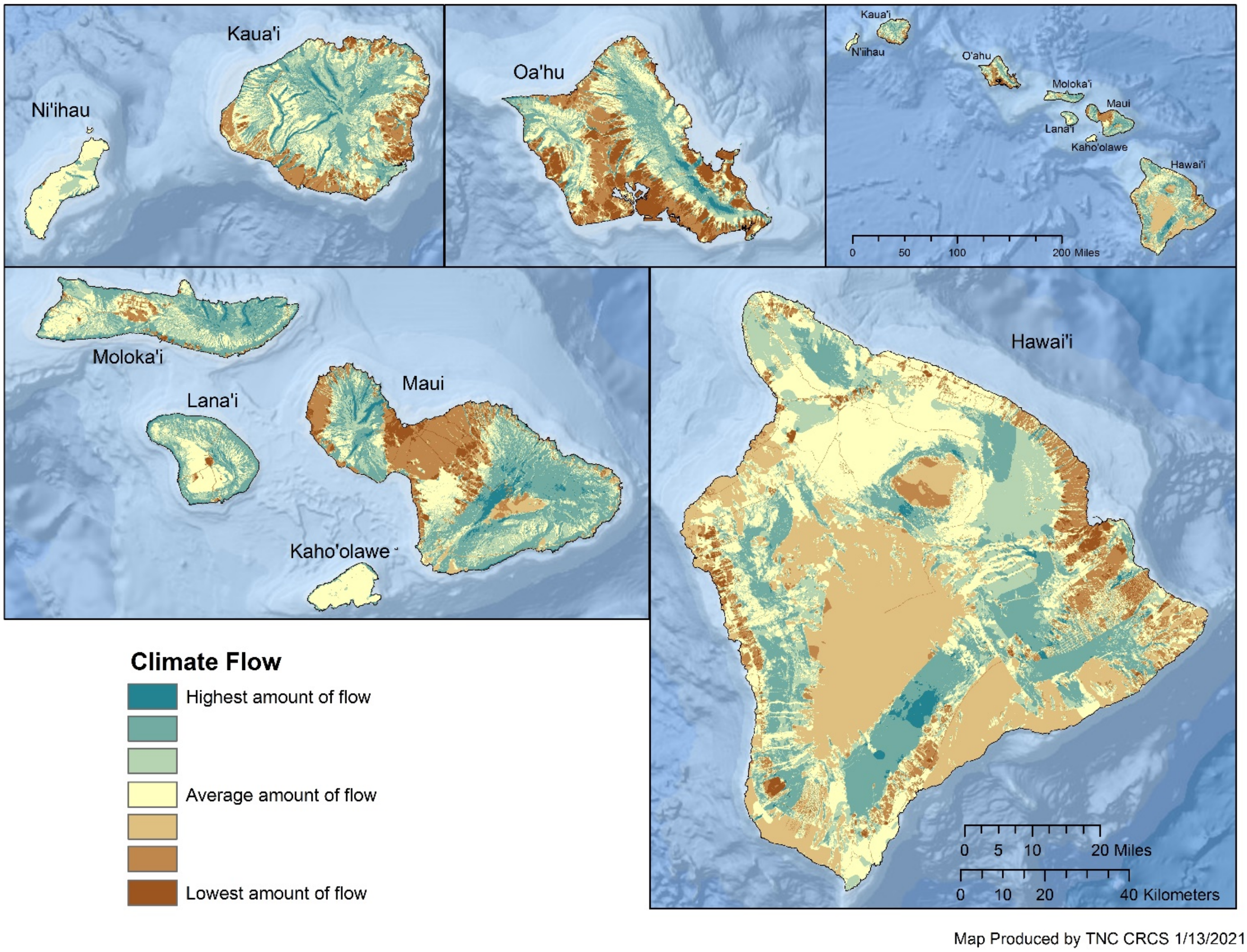


Figure 5.4: The Climate Flow Model for the Hawaii Study area.



Results and Patterns

The map of wall-to-wall climate flow applied to the anthropogenic resistance grid highlights areas of highest flow in dark blue, areas of moderate flow in medium blue, and areas of blocked or low flow in brown (Figure 5.4). As mentioned, Hawaii is a very natural landscape; average areas of flow allow for a good amount of flow through the landscape.

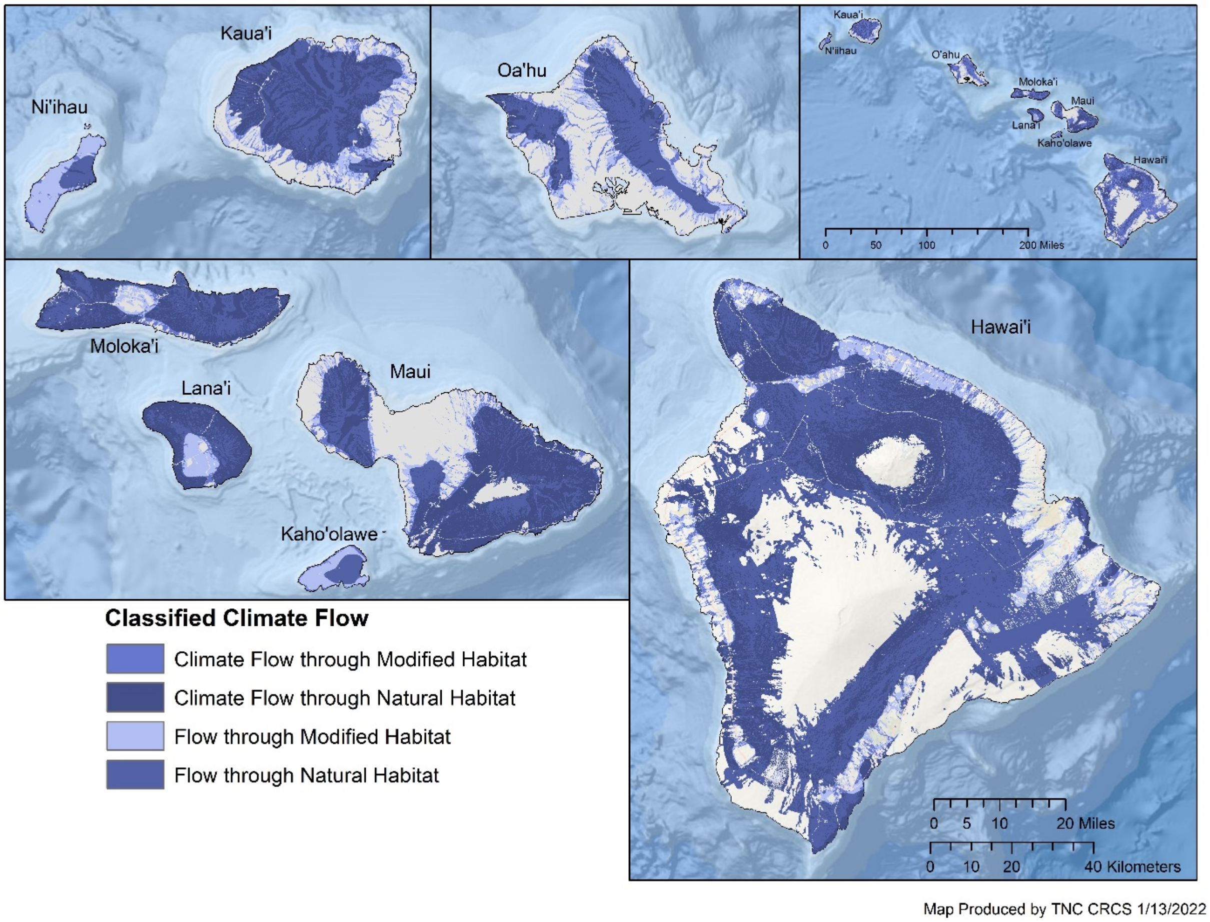
A particularly useful feature of the wall-to-wall results is that they reveal spatial patterns in current flow that reflect how the human-modified landscape is configured. The results allow you to identify where population movements and potential range shifts may become concentrated or where they are well dispersed, and it is possbile to quantify the importance of an area by measuring how much flow passes through it and how concentrated that flow is. We used stratified high flow areas by local conectedness scores to identify high flow areas in intact areas and areas were flow gets concetrated because of human modification. In Hawaii we identified three prevalent flow types found here each suggest a different conservation strategy (Figure 5.5):

Diffuse flow through Natural Habitat: areas that are extremely intact (Local Connectedness >500) and consequently facilitate high levels of dispersed flow that spreads out to follow many different and alternative pathways. A conservation aim might be to keep these areas intact and prevent the flow from becoming concentrated. This might be achievable through land management or broad-scale conservation easements.

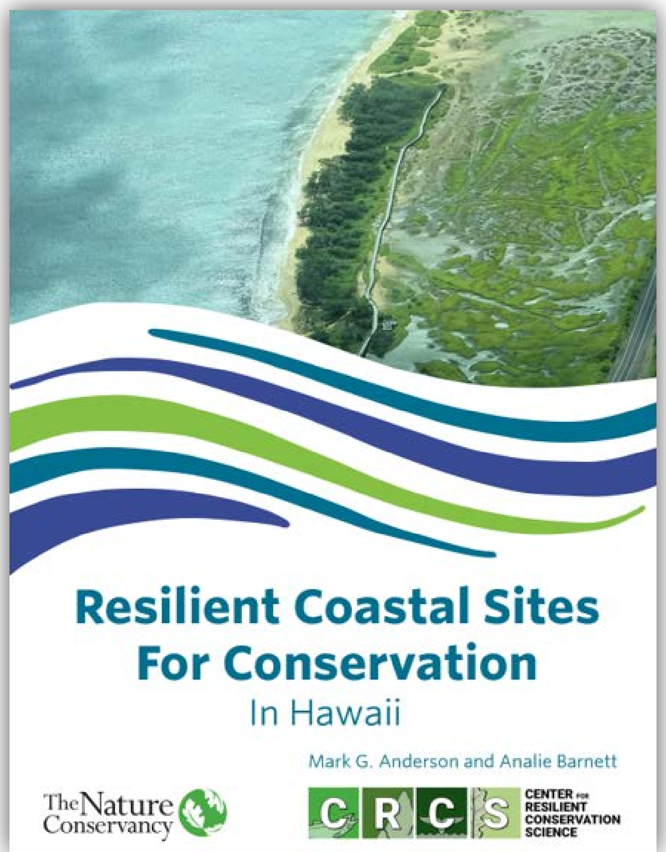
Concentrated flow through Modified Habitat: areas where large quantities of flow are concentrated through a narrow area due to human modifcation (Local Connectedness<500). Because of their importance in maintaining flow across a larger network, these pinch points are good candidates for land conservation.

Blocked/Low flow: areas where little flow gets through and is consequently deflected around these features. Some of these might be important restoration areas where restoring native vegetation or altering road infrastructure might reestablish a historic connection.

Figure 5.5: Catagorized Climate Flow. Darkest purple is climate flow (upslope or downslope) through natural habitat. Slightly lighter purple is high anthropgenic flow through natural habitat. The lightest two purples that ring around the coasts of the islands are high flow areas through modified habitat.



Coastal Resilience



As part of this project, we performed a separate analysis on the resilience of coastal systems subject to sea level rise. The analysis looks at each tidal complex a determines if it has suitable adjacent area to migrate into and whether the processes are in place to likely facilitate that migration under various sea level rise scenarios. Of course, Hawaii has special challenges related to its extensive shoreline and unique anchialine pools: brackish water environments that form in lava fields near the ocean. We recommend interested user read the report for details.

One of the products of the resilient coastal site analysis is a resilience score for every tidal complex as well as for its adjacent migration space. Migration space areas associated with an above average scoring tidal complex were incorporated into the final resilience map as an override on cells on the coast. These indicate areas important to conserve for coastal resilience.

Read the report at: http://www.nature.org/HIcoast

CHAPTER 6

INTEGRATION: BUILDING A RESILIENT AND CONNECTED NETWORK (RCN)

We integrated the three themes developed in previous sections of this report into a single network based on:

- **Site Resilience** (Chapter 2) based on microclimates and local connectedness applied to every geophysical setting within ecoregions and adjusted by macroscale processes. These criteria ensured that the network was designed around representative areas of every environment where species could persist due to the site's connected climatic diversity.
- **Recognized Biodiversity Value** (Chapter 3) based on agency and NGO portfolios of critical sites for biodiversity. This ensured that the network contained the full spectrum of current diversity features such as intact habitat, critical species populations, and rare or exemplary natural communities.
- **Climate Flow** (Chapter 5) based on an analysis of circuit flow across a landscape of variable resistance as defined by the arrangement and resistance of land uses, weighted by key upslope, northward and riparian corridors. The idea was to use the natural flow patterns in designing the network by selecting resilient and biodiverse sites that reinforced or enhanced those patterns

We did not set a numeric acreage goal for this prioritization, but we aimed to identify the portion of all the resilient areas that were the most connected and diverse, and by implication, the most critical to protect. The network is designed to represent resilient examples of all the characteristic environments of the region while maximizing the current biodiversity and climate flow contained within the network. By building the network around the natural flows that allow species populations to shift, and identifying representative resilient sites situated within those pathways, the network is specifically configured to sustain biological diversity while allowing nature to adapt and change.

The results delineate a resilient and connected network that covers **35% (1.4 million acres)** of Hawaii plus another **1.5% (62 thousand acres)** of resilient only land (Figure 5.6 and 5.7**).** Just under three quarters of the network (71%) met all three criteria: flow, confirmed diversity, and resilience. The rest of the area met at least two criteria: flow and resilience (25%) or confirmed diversity and resilience (4%). The breakdown of the network compared to the total land area of the region was as follows:

Resilient and Connected Network	**35%**
o Resilient Climate Flow with Recognized Biodiversity	11%
o Resilient Climate Flow through Natural Habitat	4%
o Resilient Flow through with Recognized Biodiversity	13%
o Resilient Flow through Natural Habitat	3%
o Resilient Flow through Modified Habitat (all types)	3%
o Resilient w Recognized Biodiversity	1%
o Resilient Coastal Migration Space	0.2%

(Note: Pioneer Lava is Appx. 19% of the study area)

In total, the network represents: resilient examples of all geophysical settings, contains the resilient portions of 1 million acres of sites identified by TNC/SWAP portfolios for biodiversity, and includes over 1.3 million acres of areas identified for regional flow in a changing climate.

Figure 6.1: Resilient and Connected Network (Simple). This map shows the resilient areas that met criteria for confirmed biodiversity, climate flow or both. The network covers 35% of the region and captures 96% of all the resilient sites.

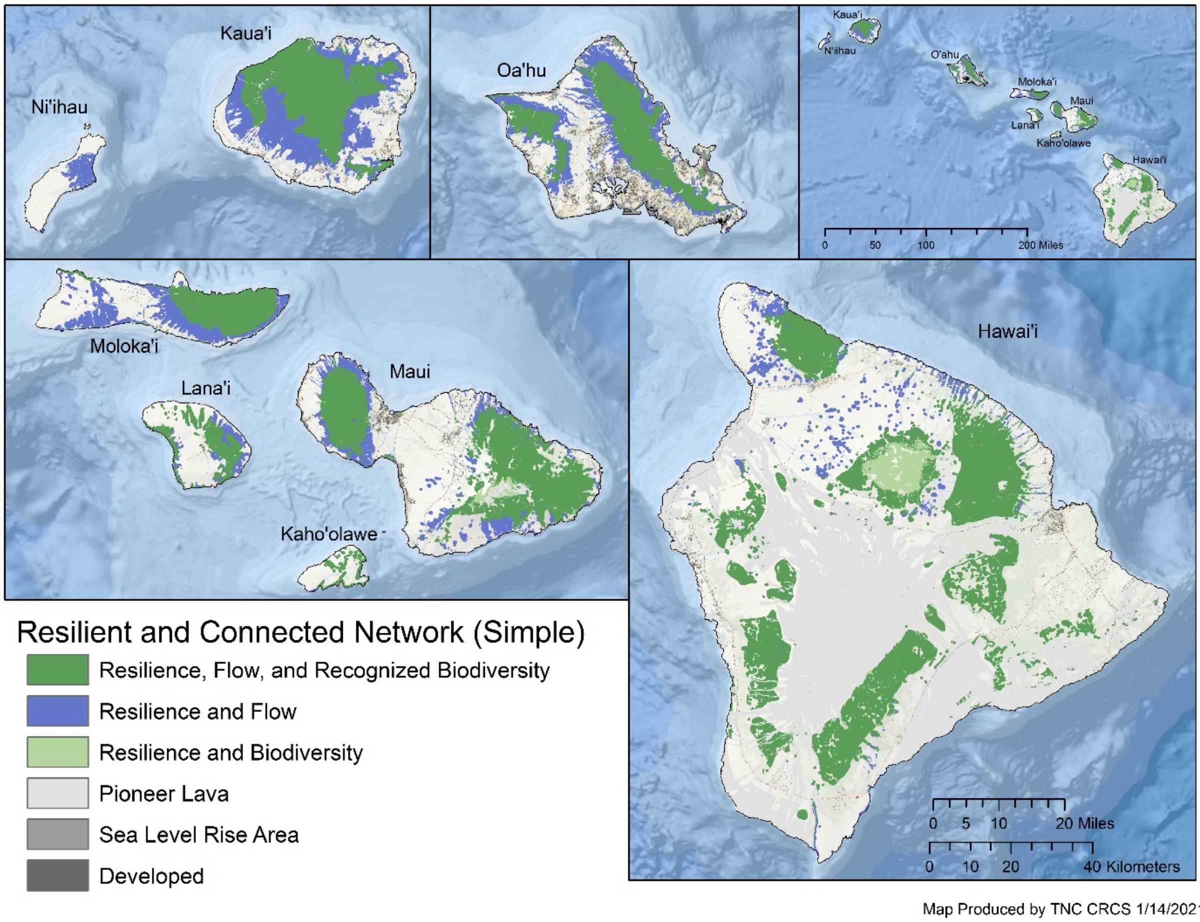
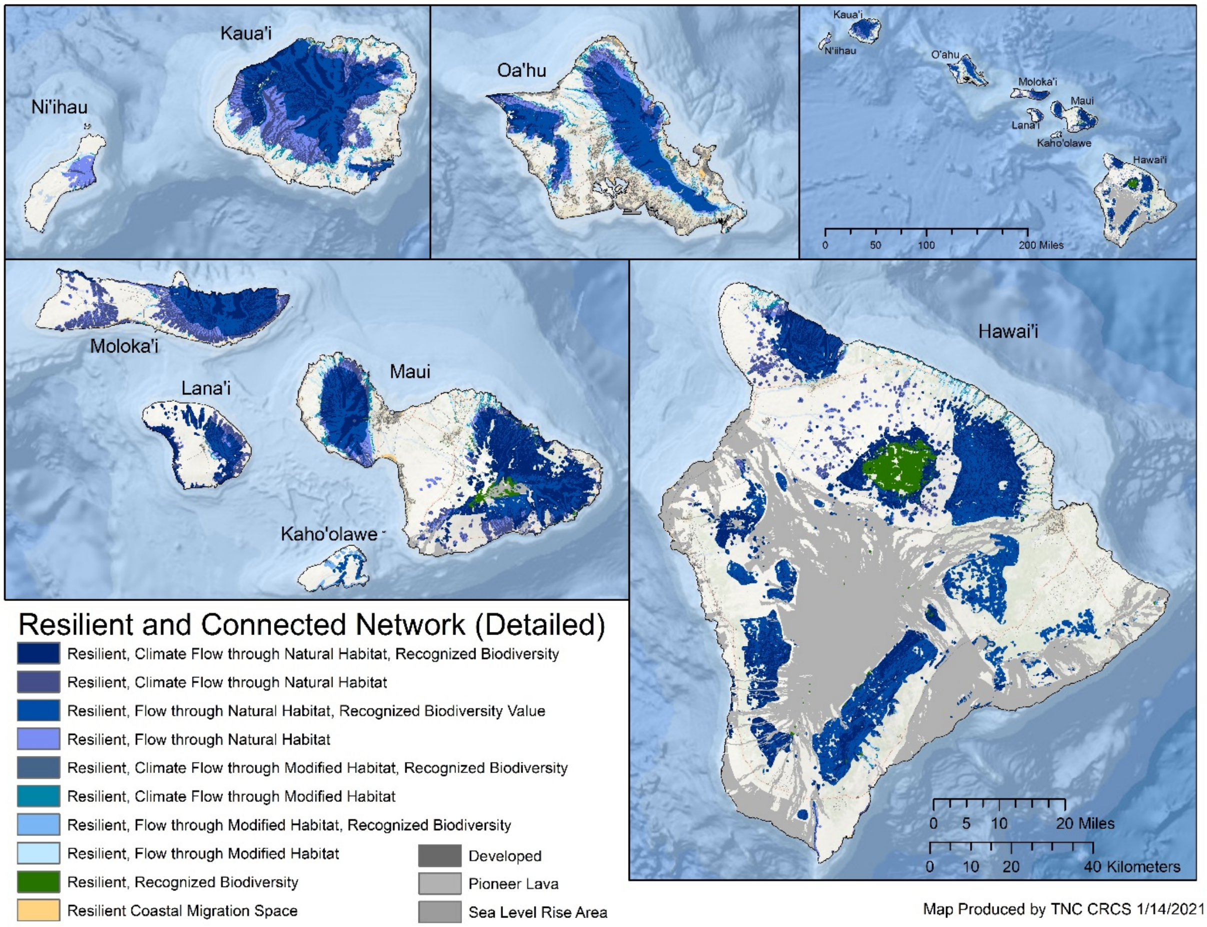


Figure 6.2: Resilient and Connected Network (Detailed). This map shows the resilient areas that met criteria for confirmed biodiversity, climate flow or both. The network covers 35% of the region and captures 96% of all the resilient sites.



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