

Remotely sensing for restoration: A scalable framework for tracking conservation outcomes and ecosystem resilience on islands

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Abstract

Removing invasive species from islands is one of the most effective conservation strategies globally, yet the broader ecosystem and climate co-benefits of such interventions remain poorly quantified as long-term monitoring is uncommon, especially on remote islands. We developed a globally scalable, spatially explicit framework that uses Landsat satellite data to track ecosystem change following conservation interventions on islands. Using c. 40 years of observations across five ecologically diverse islands, we evaluated trends in woody cover, vegetation moisture (NDMI), and productivity (NDVI, EVI, MSAVI2). We used interrupted time-series analyses to assess the effect of invasive species removal and native species reintroductions on remotely sensed indices and validated these trends against in-situ vegetation data. Vegetation responses were widespread and heterogeneous across and among islands, reflecting varying extents of initial vegetation damage and differences in topographic gradients and adaptive management histories. Woody cover generally exhibited strong positive responses, particularly on islands where invasive herbivores had been removed, while changes in vegetation moisture and productivity often were spatially restricted and were moderated by elevation or landcover. Across study systems, our remote sensing trends broadly were consistent with findings from prior field and remote sensing studies, while also revealing patterns in inaccessible areas. To support real-world decision-making, we developed an open-access web application that enables natural resource managers to visualize trends and download spatial datasets. Our findings highlight the power of remote sensing to overcome monitoring barriers on remote islands and provide a new capability for tracking and guiding ecosystem change at scale.

Introduction

Islands are biodiversity hotspots as their ecological communities evolved in isolation from continental forces, yielding some of the highest rates of endemism globally (Kier et al. 2009; Tershy et al. 2015; Whittaker and Fernández-Palacios 2007). However, the evolutionary isolation of these communities means they tend to be highly vulnerable to disturbance (Courchamp et al. 2014; Kier et al. 2009). Invasive species are among the most damaging threats to native island biota (Bellard et al. 2016; Courchamp et al. 2014). Many endemic island communities have few, if any, native predators, allowing the rapid expansion of invasive populations in the absence of top-down pressures. Once established, invasive species disrupt ecosystem processes that are key to island biodiversity, such as reducing exogenous nutrient subsidies, altering pollination dynamics, and limiting seed dispersal (Maron et al. 2006; Rogers et al. 2017; Traveset and Richardson 2006; Wolf et al. 2018; Young et al. 2010). These impacts lead to long-term ecological degradation through the conversion of native vegetation communities into invasive-dominated systems, and place endemic species at risk of extinction.

Invasive species removal programs have emerged as a critical conservation tool, with > 1,500 removal attempts globally (DIISE 2019; Jones et al. 2016; Spatz et al. 2022). These interventions yielded widespread success in protecting biodiversity, with many native faunal and floral populations exhibiting rapid demographic and distributional rebounds (Brooke et al. 2018; Jones et al. 2016). Once invasive

species have been removed from islands, managers can consider priority habitat restoration, reintroduction of extirpated taxa, and translocations of threatened species from still-invaded islands (Hennessy and Gibbs 2022; Hutton et al. 2007; Parker et al. 2023).

There is growing evidence that invasive species removals also function as nature-based solutions for climate resilience (Jones et al. 2025; Kappes et al. 2021). Eliminating invasive taxa that suppress native vegetation, whether through direct (e.g., herbivory) or indirect (e.g., loss of ecosystem engineers, soil erosion, reduced seedling recruitment) effects can reinstate seedling recruitment (Nogales et al. 2024) and catalyze forest regeneration (Hart et al. 2020). The subsequent recovery of native plant communities has been linked to improved ecosystem function, including increased plant biomass (Miller-ter Kuile et al. 2021), enhanced nutrient cycling (Benkwitt et al. 2021), and soil stabilization (Cleeland et al. 2020; Ficetola et al. 2018). These functions support climate resilience through canopy cover and moisture retention, which buffer against temperature extremes, regulate water availability, and promote carbon sequestration (Honzák et al. 2024; Kappes et al. 2021; Longley-Wood et al. 2022).

Yet, islands largely are absent from global assessments of climate-relevant ecosystem change (e.g., forest ecosystem integrity, Tierney et al., 2009; Grantham et al. 2020; Hansen et al. 2021). Many tools used to evaluate nature-based climate solutions rely on coarse resolution metrics of deforestation or biomass loss (Gao et al. 2020; e.g., Baccini et al. 2012), which fail to capture the more gradual and spatially heterogeneous degradation of vegetation structure and function caused by invasive species. The pernicious effects of invasive species can erode ecosystem integrity over decades without triggering detectable forest loss signals (Aquino et al. 2022; Asner et al. 2008). Although these changes often are subtle, they nonetheless undermine key attributes of ecosystem integrity and their corresponding climate-regulating functions. However, we lack specific knowledge of how conservation intervention programs impact vegetation, as less than 20% of island interventions incorporate long-term monitoring plans to quantify outcomes (Bird et al. 2019; Brooke et al. 2018; Jones et al. 2016; Towns 2018; D. J. Will *unpubl. data*). To understand the impact on islands, there is a clear need for better tools that are cost efficient and timely, take advantage of publicly available data layers, and are sensitive to subtle changes in vegetation. This is especially true in the face of limited conservation dollars, restricted access, and increasingly ambitious global environmental goals, as additional conservation intervention to ameliorate arrested vegetative function will increase programmatic costs.

To understand the ecological outcomes of past conservation interventions and inform future restoration efforts on islands, we developed a globally consistent and scalable framework to evaluate vegetation change. Our objectives were to: (1) quantify the spatially explicit trends of vegetation change on islands, (2) validate remotely sensed trends using in-situ monitoring data, and (3) demonstrate the utility of these data to inform conservation action at a global scale. We applied this framework to five study islands with documented post-intervention vegetation responses to restoration efforts and analyzed temporal trends in five remotely sensed vegetation indices over a c. 40-year period (1984–2023). This approach provides a pathway to assess the long-term ecological impacts of island restoration worldwide.

Methods

Study islands

We explored the responses of vegetation to conservation interventions on five islands encompassing a range of ecoregions. We chose islands that had known dates and locations of interventions where management was expected to result in vegetation change (e.g., invasive species removals, native species repatriations), had in-situ vegetation monitoring programs, and in many cases had previously used remote sensing to analyze change (Table S1). Study islands included Palmyra Atoll, a USA minor outlying territory; Santa Rosa and Santa Cruz islands in the California Channel Islands, USA; Isla Pinzón, Islas Galápagos, Ecuador; and Macquarie Island, Tasmania, Australia (Fig. 1, Table 1; Supplemental Methods: Study islands & vegetation change).

Table 1

Brief descriptions of vegetation impacts, example management goals, and interventions for the five study islands.

Island, Archipelago (coordinates), area	Vegetation damage*	Management		
		Example goal	Invasive species removal(s)	Native species augmentation(s)
Palmyra Atoll, Northern Line Islands (5°53'N, 162°04'W) c. 3 km ²	Black rat (<i>Rattus rattus</i>) halted seedling recruitment; monodominant copra stands	Realign vegetation for rainforest-to-reef resilience	Black rat (2011); <i>Cocos nucifera</i> (2019 – ongoing)	Native forest regeneration (2019 – ongoing)
Santa Rosa Island, US Channel Islands (33°58'N, 120°06'W) c. 215 km ²	Extensive browsing and grazing damage, denuding segments of islands, soil loss on Santa Rosa	Create climate refugia through the restoration of cloud forest	Pig, <i>Sus scrofa</i> (1993); domestic cattle, <i>Bos taurus</i> (1998); elk, <i>Cervus elaphus nelsoni</i> (2011); mule deer, <i>Odocoileus hemionus</i> (2015)	Island oak, <i>Quercus tomentella</i>
Santa Cruz Island, US Channel Islands (34°00'N, 119°43'W) c. 250 km ²		Create climate refugia through restoration of oak woodlands	Sheep, <i>Ovis aries</i> (1990, 2000); domestic cattle (1989); pig (2007)	
Isla Pinzón, Islas Galápagos (00°36'S, 90°39'W) c. 18 km ²	Black rat halted tortoise recruitment, indirect vegetation modification	Reintroduce and reinstate population dynamics of a megaherbivore	Black rat (2012)	Pinzón giant tortoises, <i>Chelonoidis duncanensis</i> (near annually since 1970)
Macquarie Island	European rabbit (<i>Oryctolagus cuniculus</i>) grazing of tussock and	Seabird habitat management	Goat, <i>Capra hircus</i> (1957); domestic cat, <i>Felis catus</i>	
*Reviewed in Supplemental Methods: Study islands & vegetation change and Table S1.				

Island, Archipelago (coordinates), area	Vegetation damage*	Management		
		Example goal	Invasive species removal(s)	Native species augmentation(s)
(54°37'S, 158°51'E) c. 130 km ²	herbfields; die-back of <i>Azorella macquariensis</i>		(2000); black rat (2011); house mouse, <i>Mus musculus</i> (2011); European rabbit (2011)	
*Reviewed in Supplemental Methods: Study islands & vegetation change and Table S1.				

Remote sensing

Using satellite images collected by the NASA-USGS Landsat program (c. 30 × 30 m native resolution; hereafter, 30-m pixel) (Wulder et al. 2016), we derived five indices to quantify vegetation change following the workflow from Honzák et al. (2024) (Table S2): woody cover (WC) (Sexton et al. 2013), Normalized Difference Moisture Index (NDMI) (Gao 1996; Wilson and Sader 2002), Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1974), Enhanced Vegetation Index (EVI) (Huete et al. 1997), and Modified Soil-Adjusted Vegetation Index (MSAVI2) (Qi et al. 1994). We selected these indices to capture differing dimensions of plant community structure and function (e.g., Crichton et al. 2025; Schultz et al. 2016; Storey et al. 2016). We used WC to quantify change in woody vegetation structure and NDMI to evaluate vegetation moisture (Honzák et al. 2024; Wilson and Sader 2002). The utility of NDVI, EVI, and MSAVI2 in capturing vegetation productivity varies with surface reflectance from exposed ground substrate, moisture, and vegetative biomass, each of which differs between the five study islands. We used global ecological zones (FAO 2012) to select the most appropriate vegetation productivity index for analysis: NDVI for wet non-tropical islands, EVI for wet tropical islands, and MSAVI2 for arid and semi-arid islands (Table S3). We generated time-series of annual observations for each index (Fig. 2, Table S4).

We assessed how vegetation change varied with environmental conditions. We used the NASADEM global elevation model (Crippen et al. 2016) to derive measures of elevation (m above sea level) for all islands except Palmyra (flat terrain). We used the WorldCover 2021 landcover map from the European Space Agency (ESA) (Zanaga et al. 2022) to identify the dominant landcover type for each 30-m pixel. The ESA landcover map did not include Palmyra, so we used a landcover map from 2016 (Struckhoff 2019) and simplified landcover types to match levels used in the WorldCover 2021 classification.

For large islands, we aggregated pixels, using mean values, in all input spatial datasets for computational efficiency (i.e. Santa Cruz, Santa Rosa, Macquarie aggregated to c. 300-m pixels, Pinzón aggregated to c. 90-m pixels; Palmyra unaggregated 30-m pixels; Supplemental Methods: Data processing). Measures of remotely sensed vegetation indices were not available for each pixel in every

year (e.g., regions of the island obscured by cloud cover). Thus, we included pixels in analyses when there were at least five annual observations both pre- and post-intervention.

Statistical analyses

We assessed spatially explicit vegetative changes using an interrupted time-series analysis (Wauchope et al. 2021). We designed our approach to estimate the long-term trends and subsequent changes to the trends following invasive species removals (Figure S1). For each island separately, we analyzed WC (vegetation structure via woody cover; except Macquarie which lacks woody vegetation), NDMI (vegetation moisture), and one other spectral index (vegetation productivity). For each index, we constructed three candidate models (Table S5). The baseline model included fixed effects for: (1) time (first year in time-series set to 0) to capture the long-term background (pre-intervention) trends, (2) time since intervention (set to 0 for all years prior to intervention and increased annually post-intervention) to estimate change in the trend attributable to the intervention, and (3) a one-year lag of the index to account for temporal autocorrelation in vegetation responses. To address spatial variation in vegetation dynamics, our models included a hierarchical random effect structure. We specified a random intercept for time to account for interannual variation not explained by the fixed effects (e.g., climate anomalies), and for each pixel, we included random slopes for time and time since intervention to accommodate pixel-level variation in background trends and intervention effects. Our two other candidate models were modifications of the baseline model to explore how vegetation responses were moderated by environmental gradients. In these models, time and time since intervention interacted with landcover classification (model 2) or elevation (model 3; excluding Palmyra). We included a fourth candidate model for Pinzón, where time and time since intervention interacted with the density of a keystone megaherbivore, Pinzón giant tortoises (*Chelonoidis duncanensis*; J. P. Gibbs, *unpubl. data*; Supplemental Methods: Spatially explicit interventions). Our analytical procedures are described in the Supplemental Methods: Model structure & fitting procedures and Supplemental Methods: Model selection procedures.

To identify where and how quickly vegetation responded to management, we derived rates of change using the top-ranked models. We calculated cumulative change as the overall difference across the full time-series, while annualized change represented the mean estimated yearly rate of change. Additionally, we quantified the change in slope that occurred after the intervention to isolate the impact of invasive species removal from the underlying background trend. When top-ranked models included moderating effects of landcover classification or elevation, we derived estimates of change for each level separately and reported the mean difference and the associated 85% HPDI between levels. To identify spatial patterns of change, we examined posterior distributions for each pixel and considered there to be strong posterior support for directional change when at least 85% of the probability mass was above or below zero. We summed the area of pixels meeting this criterion and compared the extent and spatial overlap of change detected for each metric to understand whether indices tracked similar or divergent patterns of vegetation response. Our derivation processes are described in the Supplemental Methods: Model output derivation procedures.

Results and Discussion

Vegetation responses to invasive species removals were widespread within islands, yet variable between islands, reflecting the complex nature of invasive species impacts and the heterogeneous effects of conservation interventions. By applying a globally consistent, remote sensing framework, we were able to detect spatially explicit patterns of vegetation change across diverse island environments. These changes were often, but not always, linked to elevation gradients and landcover types. On islands with rugged topography, woody cover was best predicted by elevation, while on low-lying Palmyra, the baseline model provided the best fit. Vegetation moisture (NDMI) was most strongly associated with elevation for Santa Rosa, Pinzón, and Macquarie, while landcover classification better explained moisture at Palmyra and Santa Cruz. For nearly all islands, productivity (NDVI, EVI, or MSAVI2) was best predicted by elevation, except for Palmyra, where EVI was best explained by landcover types (Table S7). The suite of remotely sensed indices that we used captured both consistent and idiosyncratic patterns of vegetation change, demonstrating the utility of these data in identifying areas of strong post-intervention changes and regions where additional restoration may be required. Our approach provides a scalable framework for informing conservation action across islands globally.

Island-specific responses

Elevation frequently was a strong predictor of variation in remotely sensed indices. Most of the study islands we considered had elevation ranges exceeding 350 m from sea to peak, likely capturing a suite of environmental conditions (e.g., soil moisture, temperature, exposure) that collectively define vegetation distributions and productivity (Guo et al. 2013; Irl et al. 2016). However, the strength of these elevational patterns varied among islands, potentially also reflecting the influence of island biogeography. Continental islands, which are geographically close to and tend to have biodiversity similar to that of mainland systems, more closely mirror mainland zonation patterns than oceanic islands (Irl et al. 2016). Conversely, remote oceanic islands tend to support endemic and evolutionarily distinct ecological communities (Whittaker and Fernández-Palacios 2007), and elevational vegetation patterns may vary among islands depending on the relative importance of physiological constraints and local adaptation (Fernández-Palacios et al. 2011; Steinbauer et al. 2017; Whittaker et al. 2007).

Palmyra

We detected changes in vegetation across 68.6% of the 0.8 km² area analyzed over the 23-year monitoring period, though patterns varied in magnitude and direction across indices and landcover types. Woody cover showed modest but consistent increases (Figure S2a), with positive rates of change detected during both the pre-intervention period and full time-series (Figure S2b). These gains likely reflect the gradual structural transition in the canopy following the removal of monodominant stands of Cocos beginning in 2019, coupled with earlier ecological shifts triggered by the removal of black rats in 2012 (Longley-Wood et al. 2022; Miller-ter Kuile et al. 2021; Wolf et al. 2018). Rat removal enabled native

forest regeneration by reinstating seedling recruitment (Wolf et al. 2018), though changes in the understory remained largely obscured by the closed-canopy forest that dominates the atoll. In contrast, vegetation moisture declined across 46.0% of the land area (Figure S3a), with rates of loss apparent across the full time-series (Figure S3b). While forested areas showed a brief gain in moisture following rat removal (Figure S3b), it did not translate into sustained increases later in the time-series, perhaps indicating competition for freshwater resources during native forest regeneration, increased evapotranspiration after removing *Cocos* canopy, or other climatic effects. Similarly, productivity declined across 55.9% of the land area (Figure S4a) during the full time-series (Figure S4b), coinciding with the removal of *Cocos* and potentially also reflecting the physiological demands of early successional growth. Although woody cover increased slightly, the concurrent declines in moisture and productivity suggest that the regenerating forest may be experiencing competition for light, nutrients, and water. These patterns are consistent with observations in other tropical forest systems, where competition for resources during early growth can lead to short-term physiological stress prior to canopy maturation (Wright 2002).

Santa Rosa

Vegetation change was evident across 61.2% of the 204.0 km² area of Santa Rosa included in analysis, with patterns reflecting both ecological change and historical land use. Over the full c. 40-year monitoring period, 54.6% of the land area on Santa Rosa increased in woody cover (Figure S5a), with the greatest rates of increase in the years after all invasive herbivores were removed (Figure S5b). Elevation strongly moderated these c. 40-year trends: on average, cumulative woody cover increased by 0.88% (85% HPDI: 0.39% – 1.49%) in low elevations, 1.18% (85% HPDI: 0.55% – 1.85%) in mid-elevations, and 1.38% (85% HPDI: 0.76% – 2.14%) in high-elevation areas. Cumulative gains in woody vegetation may be partially attributed to the legacy of historic browsing and grazing pressure, as steep slopes and ravines were less accessible to herbivores, allowing remnant vegetation to persist and respond quickly to their removal (Allen 1996; Summers et al. 2018; Thomson et al. 2022). Consistent with these results, a trend analysis of long-term in-situ monitoring data from Santa Rosa spanning 1990–2018 reported increasing cover of native shrubs and trees, especially *Arctostaphylos* spp. and *Salix lasiolepis*, and positive covariation between shrub cover and time since the removal of cattle in 1998 and elk in 2011 (Starceovich et al. 2025). However, this analysis also found that time since deer removal in 2015 negatively covaried with shrub cover, which could be related to the 2012–2016 California drought that may have been the driest four years of the previous 1,200 (Dong et al. 2019). Additional restoration projects, including cloud forest restoration efforts by the National Park Service and partners (Rastogi et al. 2016; Woolsey et al. 2018), are likely reinforcing the elevational patterns we detected.

In contrast, indices of vegetation moisture and productivity showed little evidence of sustained change. Vegetation moisture remained stable across most elevations, with only 3.6% of the land area increasing in NDMI (Figure S6a). Moisture briefly increased in low elevations after the removal of all invasive herbivores, though it did not persist over time (Figure S6b). Similarly, vegetation productivity increased

across just 1.7% of the land area (Figure S7a) with a transient gain at low elevations that also failed to result in sustained increases to productivity through time (Figure S7b). While elevation was a strong moderator for vegetation moisture and productivity, the absence of consistent directional trends along elevation gradients suggest that these metrics may reflect localized patterns of disturbance and recovery. For example, after herbivore removal, high-moisture riparian areas may rebound quickly, and, from a remotely sensed perspective, reach saturation in moisture and productivity compared to upland sites that are comparatively more moisture-limited. This notion is consistent with native grass and forb cover positively co-varying with water balance metrics, such as soil moisture, actual evapotranspiration, and dew within Channel Islands National Park (Starcevich et al. 2025). Additionally, elevated vegetation moisture and productivity along the northern coast may reflect the influence of fog intensity and fog water capture by Torrey pine (*Pinus torreyana*) woodlands and in the Black Mountains. Woody cover can facilitate fog interception and increase water availability that could enhance both vegetation moisture and productivity (Woolsey et al. 2018). This feedback loop may become increasingly important as vegetation structure develops and creates surface area for intercepting fog.

Santa Cruz

Santa Cruz had some of the most spatially extensive and multifaceted vegetation changes among the study islands, with change detected across 87.9% of the 240.7 km² area analyzed. Over the full 39-year monitoring period, 49.6% of the land area increased in woody cover, 20.9% decreased in vegetation moisture, and 51.3% increased in productivity. Woody cover generally increased across the full time period (Figure S8a), though gains were more pronounced and consistent on the western 90% of the island (Figure S8b, c), where sheep had been removed for nearly a decade before the remaining sheep were removed from the eastern 10% of the island.

Using repeated transect surveys, Beltran et al. (2014) reported a 23% total increase (c. 0.8% annually) in overstory woody cover on the high elevation, south-facing slopes of Picacho Diablo over 28 years (1984–2012) following sheep removal. For comparison, the subset of high elevation areas (≥ 352 m above sea level) on the western side of the island during 1990–2007 (i.e. the post-sheep/pre-pig removal period) indicated a mean cumulative change in woody cover by -0.16% (85% BCI: -0.19% – -0.12%; corresponding to mean - 0.03% annually, 85% BCI: -0.05% – -0.01%). Differences in spatial extent (Picacho Diablo vs. entire western property), sampling resolution (30-m transect sampling points approximating 0.03% of c. 300-m pixels), and sampling methodology (human estimation of overstory vs. remote sensing of all woody vegetation signatures) likely account for this apparent discrepancy, underscoring the importance of methodological context when interpreting vegetation change. While we differ in the rate of change, our estimate that 49.6% of the island increased in woody cover across the full time-series is comparable to Beltran et al. (2014)'s estimation of 51.5%, providing support for an overall increase in the extent of woody cover. Notably, our analysis, which extends to 2023, suggests that island-wide gains in woody cover plateaued. This may indicate that the passive response of woody cover has reached a limit under current conditions and that any further increases in woody cover require active restoration interventions.

Responses of vegetation moisture were comparatively spatially restricted across Santa Cruz (Figure S9a). On the western side, forested areas showed clear gains in vegetation moisture (Figure S9b), though we did not detect evidence of change elsewhere, and there were no clear and consistent patterns of change after invasive species removals (Figure S9b, c). This spatial heterogeneity may reflect the uneven effects of herbivory, oceanographic effects, and greater fog likelihood moving west across the northern Channel Islands. The lack of consistent trends in vegetation moisture suggest that vegetative water stress may be influenced by other external factors (e.g., biophysical properties, climate). Vegetation productivity was more consistent across the island (Figure S10a), with slight gains across most elevations in the years after pig removal (Figure S10b, c). Areas of decline on the 10% easternmost extent generally correspond with the area damaged in the May 2020 Scorpion fire (C. B. Williams, *pers. obs.*); fire history may help explain heterogeneity in this system.

Pinzón

We detected changes in vegetation across 48.8% of the 13.8 km² area analyzed at Pinzón, and this island had the most spatially limited response to restoration efforts in our study. Across the full 27-year monitoring period, woody vegetation cover declined across all landcover types (Figure S11a). Although we detected positive changes when rats were removed (Figure S11b), these increases were not sufficient to offset prior losses. However, the overall rate of woody cover decline slowed after rat removal, suggesting that rats reduced seedling recruitment (Clark 1981, cf. Hamann 1981; van der Werff 1978). While Pinzón's elevational range is comparable to the other larger islands in this study, woody cover did not vary meaningfully with elevation. This is consistent with broader island biogeographic patterns for oceanic islands, where treeline elevations often are lower and less strongly structured by elevation relative to continental systems (Irl et al. 2016).

Although woody cover declined, vegetation moisture and productivity remained largely unchanged. Vegetation moisture exhibited minimal overall change with only 0.5% of the land area had increased NDMI (Figure S12a) and no meaningful changes with rat removal (Figure S12b). Similarly, productivity exhibited little change across the full 27-year monitoring period. Positive changes were restricted to low elevations (Figure S13a) and productivity did not vary with rat removal (Figure S13b). This apparent 'decoupling' may reflect the inherently low productivity of xeric vegetation communities, where water limitation constrains plant growth (Fischer and Turner 1978). Localized moisture inputs from seasonal garúa (fog) likely provide some buffer from extreme aridity around the island coast, and may explain the weak relationship observed for productivity and elevation.

Macquarie

We detected changes in vegetation across 93.5% of the 128 km² area considered in analysis. Across the full 23-year monitoring period, vegetation moisture increased across the island (Figure S14a) though annual rates of change occurred in high elevations (Figure S14b). In contrast, productivity largely was

stable; only 10.8% of the land area increased in NDVI (Figure S15a) and there were no substantial gains that we could detect after the removal of all invasive species (Figure S15b).

Our study overlaps with a period of widespread dieback of *Azorella macquariensis*, an endemic cushion plant that dominated the island's fjeldmark communities (Bricher et al. 2013; Kitchner and Harris 2013). The species is restricted to the island's high altitude, upland plateau. The death of *Azorella macquariensis* plants is with reduction in summer water availability, increased wind and sunshine, and the subsequent changes to plant evapotranspiration, coupled with a pathogenic infection (Bergstrom et al. 2015; Dickson et al. 2021). While we found positive increases in vegetation moisture, the ecological outcomes of these changes likely vary with the dominant vegetation cover. A given NDMI value could indicate adequate moisture for warm-adapted or drought-tolerant plant species, while reflecting physiological stress or moisture limitation in cold-adapted, moisture-sensitive taxa.

This divergence between vegetation moisture gains and stable productivity likely reflected transitions among dominant plants (Fitzgerald et al. 2021; Kirkpatrick 2009). While the widespread dieback of *Azorella macquariensis* could have reduced productivity signals, the concurrent regime shift to grasslands may have offset any apparent declines, resulting in little net change in NDVI despite substantial vegetation turnover (Bergstrom et al. 2021; Fitzgerald et al. 2021). Areas with substantial gains in productivity were concentrated along coastal penguin colonies (Pascoe et al. 2020, 2022) where tussock grasses are the dominant vegetation (Fitzgerald et al. 2022). These areas may represent localized hotspots of grass recovery, supported by the release from rabbit grazing and enhanced nutrient availability from seabird subsidies. Seabirds enrich ecosystems through nutrient inputs (Jones et al. 2025; Sandin et al. 2022) which boost isotopic signatures and productivity in primary producers (Graham et al. 2018; Grant et al. 2025).

Congruence of remote sensing indices

For some islands, we observed spatially consistent signals of change across all remotely sensed indices, indicating strong, integrated shifts in vegetation structure, moisture, and productivity. However, these fully concordant changes were relatively limited in spatial extent, typically encompassing a fraction of the land area analyzed. In contrast, the majority of changes were captured by just one or two indices, pointing to asynchronous or functionally distinct vegetation responses. Structural changes in woody cover were the most commonly detected, accounting for some of the largest land areas affected across islands, while functional measures of moisture and productivity tended to identify comparatively smaller areas. This result highlights the possibility that some functional responses may precede other changes. By jointly analyzing multiple indices representing differing dimensions of ecological function, we were able to disentangle varying ecological processes to uncover both subtle and divergent patterns of change that would likely have been obscured in single-metric analyses. Our multi-dimensional approach provides a more nuanced understanding of vegetation change trajectories.

Conclusions & management implications

Using a globally applicable framework, we were able to provide spatially explicit insights about changes in vegetation structure and function following conservation interventions on a diverse set of island ecosystems. Our results not only confirmed patterns reported in previous remote sensing and in-situ studies conducted on these islands, but also provided new insights into changes in areas that were inaccessible or difficult to reach on the ground.

These insights have immediate management applications. On Pinzón, our results can guide the selection of reintroduction sites based on areas that show the strongest post-intervention recovery. On Santa Cruz, spatial patterns in vegetation indices highlight zones where passive recovery may be insufficient, allowing for targeted active restoration. By measuring changes in indicators strongly associated with ecosystem resilience (woody cover, vegetation moisture, and productivity), these insights give conservation practitioners new ways to manage the trajectories of ecosystem recovery across space and time, and quantify the benefits of their actions.

Clear vegetation responses following invasive species removal demonstrate the effectiveness of these conservation interventions, even in ecosystems with slow-growing or physiologically stressed plant communities. However, the diversity of responses across islands, and even within systems, underscores the need for monitoring spatially explicit vegetation changes. Remotely sensed indices, especially when multiple indices are used, can provide a scalable and consistent method of assessing vegetation change across challenging, remote landscapes. Coupling remote sensing analyses with in-situ field studies provides an holistic understanding of ecosystem change. While plot- or transect-based studies can offer valuable insights into localized changes and remotely sensed indices can capture broad spatial trends, their integrated interpretation is essential to understanding widespread ecological change. Incorporating additional environmental variables, such as elevation and landcover classifications, can further explain spatial variation in vegetation responses and identify the conditions associated with restoration goals. The effects of climatic variation, such as rainfall or fog moisture input, should also be considered in future studies. Though we caution that changes in structural, physiological, and functional vegetation traits may not occur simultaneously, and early indicators of recovery can precede more visually obvious gains. As recovery continues, sustained monitoring using remotely sensed indices is essential for capturing long-term trends, detecting emerging stressors, and identifying areas of limited recovery that would benefit from additional targeted intervention.

Declarations

Conflicts of Interest

The authors have no conflicts of interest to declare.

Author Contributions

CNW: investigation, methodology, formal analysis, visualization, software, validation, writing – original draft, writing – review & editing. **BJC:** conceptualization, resources, data curation, methodology, formal analysis, visualization, software, validation, writing – review & editing, supervision, project administration, funding acquisition. **LJB:** validation, writing – review & editing. **MF:** resources, data curation, methodology, visualization, software, validation, writing – review & editing. **KF:** validation, writing – review & editing. **JPG:** conceptualization, investigation, methodology, writing – review & editing, supervision, funding acquisition. **NH:** validation, writing – review & editing. **MH:** conceptualization, investigation, resources, data curation, methodology, software, validation, writing – review & editing. **AL:** validation, writing – review & editing. **AEM:** validation, writing – review & editing. **JOS:** conceptualization, investigation, resources, data curation, methodology, visualization, software, validation, writing – review & editing, supervision, project administration, funding acquisition. **JDS:** validation, writing – review & editing. **PW:** resources, data curation, methodology, visualization, software, validation, writing – review & editing. **AW:** validation, writing – review & editing. **CBW:** validation, writing – review & editing. **EW:** data curation, methodology, visualization, software, writing – review & editing. **DJW:** conceptualization, investigation, resources, methodology, formal analysis, visualization, validation, writing – review & editing, supervision, project administration, funding acquisition.

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Data Availability Statement

The data and code that support the findings of this study are available from <https://islandconservation.shinyapps.io/island-vital-signs/> and <https://github.com/Island-Conservation>.

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Figures

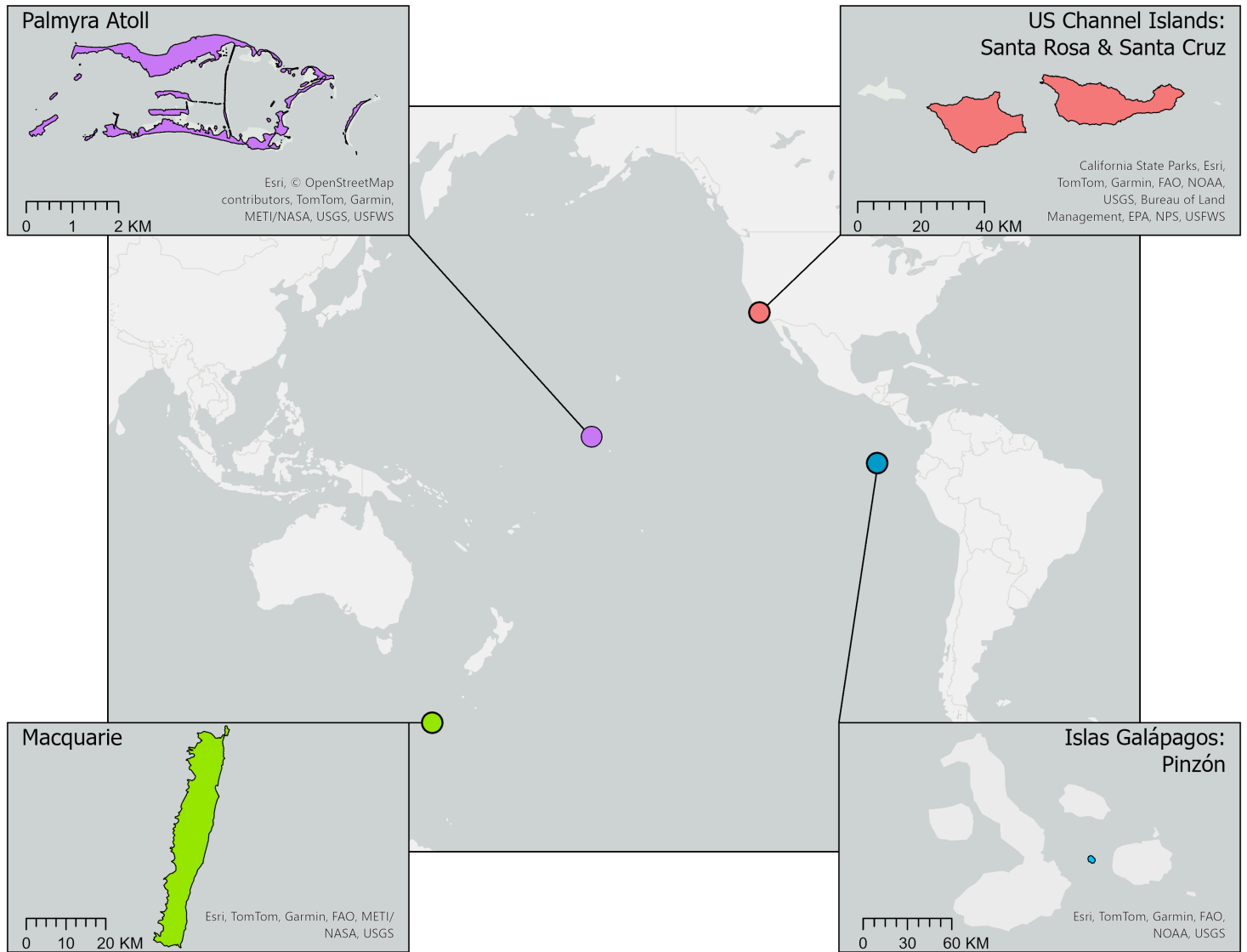


Figure 1

Figure 1. Locations of the five study islands considered in analysis (from top left, clockwise): Palmyra Atoll, US territory; Santa Rosa (left) and Santa Cruz (right) islands, US Channel Islands; Isla Pinzón, Islas Galápagos, Ecuador; and Macquarie Island, Australia.

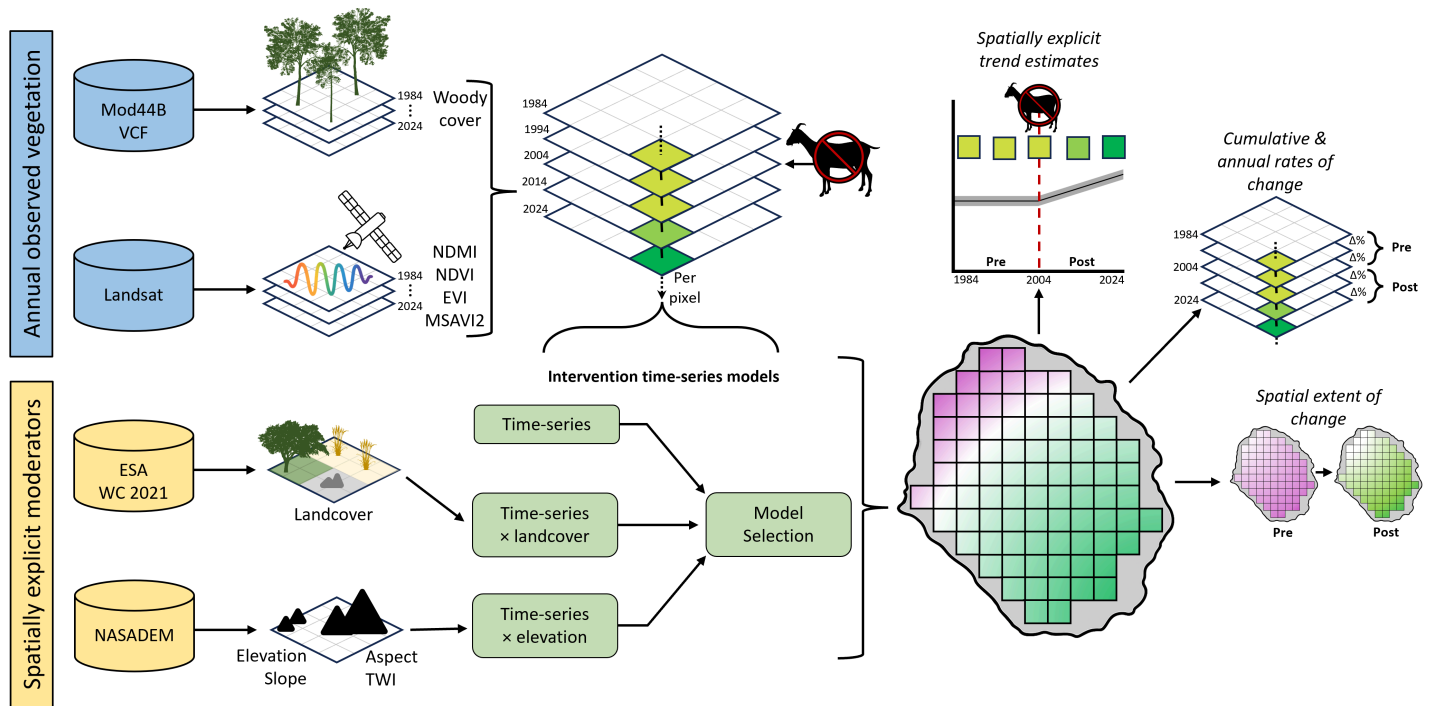


Figure 2

Figure 2. Overall workflow for evaluating and quantifying vegetation change. We generated the woody cover time-series using Mod44B Vegetation Continuous Fields (VCFs) (Sexton et al. 2013). We calculated time-series for Normalized Difference Moisture Index (NDMI) (Gao 1996; Wilson and Sader 2002), Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1974), Enhanced Vegetation Index (Huete et al. 1997), and Modified Soil-Adjusted Vegetation Index (MSAVI2) (Qi et al. 1994) using Landsat data. We analyzed time-series per pixel using an interrupted time-series analysis (Wauchope et al. 2021), and considered three models (baseline, time-series; time-series $\times$ landcover classification; time-series $\times$ elevation) using moderating data from the European Space Agency’s 2021 WorldCover data product (Zanaga et al. 2022) and NASADEM (Crippen et al. 2016). After identifying the best supported model using a Bayesian model selection procedure (Bürkner 2017; Vehtari et al. 2017), we generated island-wide rasters for estimates of trends and changes to trends that occurred during conservation interventions, cumulative and annualized rates of change before and after interventions, and quantified the spatial extent of vegetation change. Vegetation and goat (*Capra hircus*) icons are public domain (CC0 1.0) and accessed from PhyloPic.

Supplementary Files

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