Conservation Biology

Conservation Methods

Using spatially explicit, time-dependent analysis to understand how social factors influence conservation outcomes

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Abstract: Conservation across human-dominated landscapes requires an understanding of the social and ecological factors driving outcomes. Studies that link conservation outcomes to social and ecological factors have examined temporally static patterns. However, there may be different social and ecological processes driving increases and decreases in conservation outcomes that can only be revealed through temporal analyses. Through a case study of the invasion of *Falcataria moluccana* in Hawaii, we examined the association of social factors with increases and decreases in invader distributions over time and space. Over 7 years, rates of invader decrease varied substantially (66–100%) relative to social factors, such as building value, whether land was privately or publically owned, and primary residence by a homeowner, whereas rates of increase varied only slightly (<0.1–3.6%) relative to such factors. These findings suggest that links between social factors and invasion in the study system may be driven more by landowners controlling existing invasive species, rather than by landowners preventing the spread of invasive species. We suggest that spatially explicit, time-dependent analyses provide a more nuanced understanding of the way social factors influence conservation outcomes. Such an understanding can help managers develop outreach programs and policies targeted at different types of landowners in human-dominated landscapes.

Keywords: invasive species, land-use change, private lands, remote sensing, urban ecology

Uso de un Análisis Espacialmente Explícito y Dependiente del Tiempo para Entender cómo Influyen los Factores Sociales sobre los Resultados de la Conservación

Resumen: La conservación dentro de los paisajes dominados por humanos requiere de un entendimiento de los factores sociales y ecológicos que afectan los resultados. Los estudios que conectan los resultados de la conservación con los factores sociales y ecológicos han examinado temporalmente los patrones estáticos. Sin embargo, puede haber diferentes procesos sociales y ecológicos que produzcan un incremento o una disminución en los resultados de la conservación, los cuales sólo pueden ser revelados por medio de los análisis temporales. Examinamos la asociación entre los factores sociales y el incremento y la disminución de la distribución de una invasión en el tiempo y el espacio con el estudio de caso de la invasión de *Falcataria moluccana* en Hawái. A lo largo de siete años las tasas de disminución de la invasión variaron considerablemente (66-100%) en relación con los factores sociales, como el valor de construcción, si la tierra era pública o privada, y si era la residencia principal del propietario, mientras que las tasas de incremento variaron solamente un poco (<0.1-3.6%) en relación con dichos factores. Estos hallazgos sugieren que las conexiones entre los factores sociales y la invasión en el sistema

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de estudio podrían ser causados más por los propietarios que controlan a las especies invasoras existentes en lugar de ser causados por los propietarios que previenen la expansión de las especies invasoras. Sugerimos que los análisis espacialmente explícitos y dependientes del tiempo proporcionan un entendimiento más matizado de cómo los factores sociales influyen sobre los resultados de la conservación. Dicho entendimiento puede ayudar a los administradores a desarrollar programas y políticas de compromiso con la comunidad enfocadas en diferentes tipos de propietarios en los paisajes dominados por el humano.

Palabras Clave: cambio de uso de suelo, ecología urbana, especie invasora, tierras privadas, teledetección

摘要: 在人类主导的景观中开展保护需要了解社会和生态因素对保护成效的影响。目前, 将保护成效与社会和生态因素相结合的研究已经分析了当下的静态格局。然而, 可能存在一些不同的社会和生态过程推动或阻碍着保护, 它 的影响要通过时序分析才能得到揭示。我 通过对夏威夷入侵物种南洋楹 (*Falcataria moluccana*) 的案例分析, 检验了社会因素与入侵范围的时空变化 间的关系。结果表明, 在超过 年的时间里, 南洋楹减少的速率相对于社会因素 (如建筑价值、土地私有或公有、土地是否用作私有者的主要住宅) 变化很大 (66-100%), 而增加速率相对于这 因素变化却很小 (<0.1-3.6%) 。这 发现表明, 研究系统中社会因素与入侵的联系可能更多地受到土地所有者控制现有入侵物种的驱动, 而 是土地所有者防止入侵物种扩散的结果。我 认为, 基于时间的空间显式分析为研究社会因素如何影响保护成效提 了更精细的理解, 这有助于管理者在人类主导的景观中制定针对 同类型土地所有者的延 项目和政策。【**翻译: 胡怡思; 审校: 聂永刚**】

关键词: 城市生态学, 入侵物种, 土地 用变化, 私有土地, 遥感

Introduction

As urbanization increases globally, conservation programs increasingly seek to enhance biodiversity outcomes across a diversity of land uses (Dearborn & Kark 2010; Goddard et al. 2010; Cook et al. 2012). In human-dominated landscapes, the distribution of conservation outcomes may vary by environmental factors that influence habitat quality and by social factors that influence landowner action (Hope et al. 2003; Kinzig et al. 2005; Beliare et al. 2016). Landowners may influence conservation outcomes, for example, by planting native plants, keeping cats indoors, removing invasive species, or introducing invasive species (e.g., Reichard & White 2001; Goddard et al. 2010; Cook et al. 2012). The likelihood a landowner engages in these actions may vary based on landownership characteristics (i.e., the socioeconomic and property-specific characteristics of the landowner) and community and regional characteristics (Cook et al. 2012).

Given the potential for landowners to influence the distribution of conservation outcomes (e.g., native and invasive species distributions) across human-dominated landscapes, researchers have examined links between social and environmental factors and species distributions (e.g., Hope et al. 2003; Kinzig et al. 2005; Gulezian & Nyberg 2010). They identified numerous social factors associated with species distributions operating at scales ranging from the individual property to the community, such as family income, housing age, population density, and public versus private ownership (Hope et al. 2003; Decker et al. 2012). Their findings can inform conservation planning by identifying the types of landowners who or communities that are not achieving desired conservation outcomes; managers may then target outreach toward these specific groups (e.g., Metcalf et al. 2019).

The majority of existing studies have examined temporally static patterns associated with conservation outcomes in human-dominated landscapes (e.g., native or invasive species distributions measured at one point with social and ecological characteristics measured at that same or a different point) (e.g., Hope et al. 2003; Decker et al. 2012; Niemiec et al. 2018). The correlations between social factors and species distributions could be due to different social processes driving increases or decreases in species distributions over time. Greater prevalence of native species on properties at a single point could be due, for example, to landowners planting native plants or providing bird nesting boxes to increase native species over time (Goddard et al. 2010). We refer to these actions as transformative management because they involve actively improving an area to achieve a desired outcome (Table 1). Greater prevalence of native species at a single point could also be due to landowners preventing actions that would harm existing native species. For example, landowners may keep cats indoors or refrain from developing an area with existing wildlife habitat (Goddard et al. 2010). Such actions would prevent a decrease in native species populations on their property over time. We refer to these actions as preventative management because they involve engaging in management efforts to prevent change in an area (Table 1).

Lower prevalence of invasive species on properties at a single point could be driven by preventative management activities by landowners, such as cleaning vehicles and gear (Sharp et al. 2017), not purchasing invasive plants or plants that could carry invasive species (Reichard & White 2001), or reducing disturbance (Vila & Ibanez 2011) to ensure that invasive, non-native species do not

Table 1. How preventative and transformative management differentially influences losses or gains in native or invasive species over time.

Management type	*Native species distributions*	*Invasive species distributions*
Preventative	prevent losses of preexisting native species (e.g., refraining from development and keeping cats indoors)	prevent gains of invasive species (e.g., cleaning vehicles or gear or reducing disturbance to prevent the establishment of invaders)
Transformative	alter habitat by increasing the number of native species (e.g., planting native plants and providing bird nesting boxes)	alter habitat by reducing the number of existing invasive species (e.g., treating preexisting invasive plant infestations with herbicide)

establish on their property. Alternatively, lower prevalence of invasive species could be driven by landowners taking action to remove existing invasive species, for example, by applying pesticides or herbicides (Aslan et al. 2009; Niemiec et al. 2016). Because managing existing invasive species involves altering the ecosystem over time to achieve a desired outcome, these actions are transformative management (Table 1). Thus, while static analyses can help identify the types of landowners associated with greater invasive species or fewer native species who should be targeted in outreach and policy efforts, such analyses cannot inform managers on the types of behaviors (transformative vs. preventative) such groups are failing to engage in.

We argue that spatially explicit, time-dependent analyses could improve conservation planning and management by revealing whether observed associations between social factors and species distributions are due to variations in the extent of preventative or transformative management. We define spatially explicit, time-dependent analyses as studies linking social and ecological factors with changes in species distributions over space and time. Distinguishing between preventative and transformative management could inform the development of more effective conservation plans by revealing the types of behaviors (transformative vs. preventative management) that should be promoted through outreach programs for different types of landowners.

Knowing the types of behaviors to focus on is particularly important because motivating transformative versus preventative management requires different approaches. To effectively motivate behavior change, outreach programs should be designed to address the audience's specific barriers and motivations associated with a particular behavior (McKenzie-Mohr & Schultz 2014; McLeod et al. 2015). For example, landowners' decisions to control existing invasions (transformative management) may be influenced by cost, knowledge of control techniques, and perceptions of whether their neighbors will also control invaders (e.g., Aslan et al. 2009; Epanchin-Niell et al. 2010; Niemiec et al. 2016). Landowners' decisions to engage in preventative management to stop the spread of invaders may be influenced by their lack of knowledge of effective actions and perceptions that the recommended actions will not make a difference or be too difficult (Prinbeck et al. 2011). Reducing these barriers through outreach programs and policies requires varied approaches. For example, educational programs on management techniques, subsidies for supplies, and community meetings to facilitate collaboration may motivate transformative invasive species management (Niemiec et al. 2019). Tools and infrastructure for cleaning equipment, education programs discussing preventative behavior, and enforcement of regulations regarding the spread of invaders could help motivate preventative management (Prinbeck et al. 2011; Sharp et al. 2017). Thus, by clarifying whether links between social factors and conservation outcomes are driven by transformative or preventative management, results of spatially explicit, time-dependent analyses can help managers devise outreach programs and policies that may be needed for different landowner groups.

To illustrate the utility of spatially explicit, time-dependent analyses, we examined how net changes in the distribution of a highly invasive tree, *Falcataria moluccana* (FM), in Hawaii varied by landowner and by environmental, ecological, and land-use characteristics over 7 years. A nitrogen-fixing early-successional species, FM is native to the Moluccas, New Guinea, New Britain, and the Solomon Islands (Wagner et al. 1999). It was first brought to Hawaii in the mid-1900s and has spread, causing significant ecological and socioeconomic damage (Hughes et al. 2011). It out-competes and replaces native overstory tree species (Hughes & Denslow 2005), supports other highly invasive species in its subcanopy (Asner et al. 2008), and falls in high winds, causing damage to infrastructure (Butler 2014). Due to FM's significant socioeconomic impacts, landowners in Hawaii often try to reduce FM populations on their property and in their community (Niemiec et al. 2016; Niemiec et al. 2017). Changes in FM distributions may therefore be influenced by a combination of landowner actions, natural disturbance, land use, environmental mediating factors, and propagule pressure.

Methods

We quantified changes in FM cover on approximately 40,000 ha of a human-dominated landscape in the Puna District of Hawaii. We integrated spatially explicit tax map key (TMK) data on land ownership with remote-sensing data on FM cover in 2009 and 2016. We also incorporated spatially explicit data on climate, topography, soil age, and land use.

The 2009 FM map was reproduced from Niemiec et al. (2018). The map has a 2-m spatial resolution and was created from Worldview-2 satellite imagery with supervised maximum likelihood classification, extensive species-specific ground-verification data, and manual postclassification processing (Niemiec et al. 2018 & Supporting Information).

We created a 2-m resolution map of 2016 FM cover with data from the shortwave infrared imaging spectrometer onboard the Arizona State University Global Airborne Observatory (GAO), formerly the Carnegie Airborne Observatory (Asner et al. 2012; see Supporting Information for more information on data collection and processing). We used a biased support vector machine (BSVM) to classify FM from the GAO data (Baldeck & Asner 2015; Barbosa et al. 2016). For the BSVM training data set, we identified 45 fully sunlit crowns of FM trees with Google Earth, which led to 6794 FM training points. For the testing data set, we used 20,000 random points (Baldeck & Asner 2015). We tested the resulting 2016 map with field observations of 50 points with FM and 50 points without FM randomly generated from our model (Supporting Information).

To create a 2009–2016 net change map for FM, we resampled each of the 2-m resolution maps to 5-m resolution with nearest neighbor resampling for computational efficiency (at 5-m resolution, land-ownership variables were still accurately captured, whereas at coarser resolutions the boundaries between smaller properties were blurred). We gridded our study area into 16,030,786 5×5 m cells. We then took the difference between the 2009 and 2016 maps to create a change map that indicated areas of increase, decrease, and no change in FM cover (Fig. 1). Both the 2009 and 2016 maps had high overall accuracy (2009: sensitivity = 0.78, specificity = 0.94; 2016: sensitivity = 0.88, specificity = 0.94). Our use of these individual maps in combination means the change map may have lower accuracy than either the 2009 or 2016 maps in isolation. However, it is unlikely that patterns in classification errors are correlated with land ownership variables, given the complete independence of the underlying change map data with the land ownership variables.

To examine how changes in FM distribution varied by land ownership, land use, environmental, and ecological factors, we gathered spatially explicit data from Hawaii County's 2013 TMK records (publicly available from the State of Hawaii Office of Planning) on the value of any buildings on the land (indicator of landowner wealth), the size of the property, whether the property was owned by one of the ten landowners with the most property in the study region, whether a tax reduction was applied due to primary residence by a homeowner (i.e., homeowner exemption), and whether the land had a building (i.e., home) or no building on it (indicator of absenteeism). We gathered land-use data on agriculture, high-intensity development, and low-intensity development from the National Gap Analysis Program Land Cover Data 2011 (Homer et al. 2015). To calculate distance to a road, we used the Hawaii County roads layer derived from the 2000 Census (State of Hawaii Office of Planning 2013). We then calculated Euclidian distance to a road with ArcMap version 10.0. We also obtained spatially explicit data on elevation, cloud, and wind from the Climate of Hawai'i website, University of Hawai'i at Manoa (Giambelluca et al. 2014). We obtained soil ages from the Soil Survey Geographic Database (NRCS 2006). We also created a variable to measure the distance of an area to the closest FM that was present in 2009 (indicator of propagule pressure) with the Euclidian distance function in ArcMap version 10.0 and the 2009 5-m ground-level resolution FM map.

We projected each data layer to WGS 1984 UTM zone 5N and cropped each layer to have the same extent in ArcMap version 10.0. For variables obtained as shapefiles, such as all TMK land ownership data, we converted each shapefile variable to a raster with the same projection, grain size, and extent as the FM-change maps. For variables obtained as rasters, we used nearest neighbor resampling to ensure that variables had the same grain size and extent as FM-change maps. Once all variables had the same grain size, projection, and extent, we exported values for each variable for each 5-m ground-level resolution grid cell in the study area with the raster to points function in R version 3.2.1. For each binary land-ownership and land-use variable, we calculated the unadjusted mean FM decrease and increase for each level of the variable (i.e., variable = 1 and variable = 0). For each continuous variable, we calculated the unadjusted mean FM decrease and increase for each quartile of the variable.

In addition to calculating unadjusted means, we used a controlled sampling approach (Brodrick & Asner 2017) to normalize for the distribution of key covariates that might affect the distribution of FM (from Niemiec et al. 2018), including elevation, cloud cover, wind, distance to road, and distance to 2009 FM (for increase values). To calculate controlled mean values, we divided each covariate into quartiles and found the mean FM canopy cover change (increase and decrease) within that quartile. Reported controlled mean values are those of all subsample means. Controlled means thus represent mean increase or decrease by land-ownership and land-use type with equal influence across elevation, cloud cover, wind, distance to road, and distance to 2009 FM throughout the study area. We did not conduct statistical analyses to compare means because our data included the full sample of FM change in the study area; therefore, the means reported are the true population means.

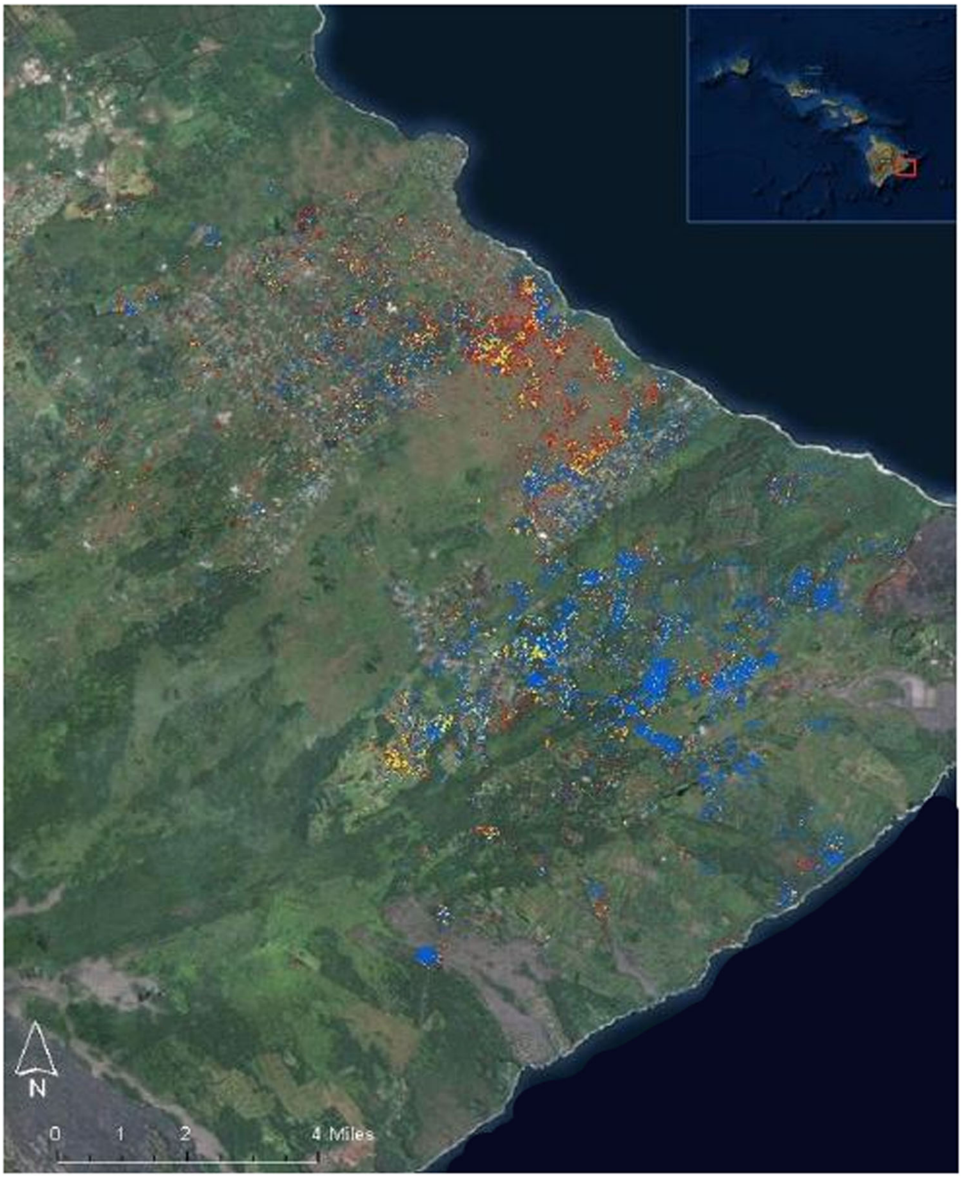

Figure 1. Map of Falcataria moluccana *(FM) change from 2009 to 2016 in the Puna District of Hawaii (red, increase in FM distributions; blue, decrease in FM distributions; yellow, areas where FM remains the same). Sources: ESRI, DigitalGlobe, GeoEye, EarthStar Geographic, CNES/Aribus DS, USDA, USGS, AeroGrid, IDN, and the GIS User Community.*

One can differentiate between preventative and transformative management by examining whether the species of interest is present in the initial period. We examined whether FM was detected in 2009 to determine the type of management that may be occurring. An area without FM in 2009 (initial period) that had FM in 2016 (final period) was an area where FM spread on its own or with the help of humans from 2009 to 2016. If humans did not engage in preventative management or invader spread and establishment occurred independent of human action or inaction, we expected patterns of spread to not be correlated with landownership variables. If patterns of species spread were associated with landownership variables, this was likely because certain types of landowners engaged in preventative management, whereas other groups did not.

We assumed an area with FM in 2009 that did not have FM in 2016 was an area where FM died due to natural causes (e.g., blow over and old age) or landowners engaged in effective transformative management (i.e., landowners controlled preexisting invader populations). We expected patterns of natural die-off to correlate with climatic and environmental conditions (which we controlled for) but to occur independent of landownership variables. Thus, correlations between decreases and landownership variables would likely be due to landowners engaging (or not) in transformative management. Although the total percent increase and decrease was likely due to a combination of natural and human-related causes, correlations between landownership variables and increases and decreases would likely be due to preventative or transformative management.

To examine socioecological processes driving preventative and transformative management, we divided our results into mean rates of decrease in areas with FM in 2009 ($n = 756{,}484$) and mean rates of increase in areas without FM in 2009 ($n = 15{,}274{,}302$). Mean rates reported were calculated as the number of cells with a decrease or increase divided by the number of cells with or without FM in 2009.

Results

Transformative Management

Falcataria moluccana cover decreased 75.03% from 2009 to 2016 in areas that had FM in 2009, a 10.7% annual net decrease in FM canopy cover and a collective FM canopy reduction of 283.8 ha. Controlled mean decreases in FM cover ranged from 66.3% to 100% across property ownership types (Table 2) (unadjusted means were similar [Supporting Information]). The mean rate of FM decrease was greater on private lands than government-owned lands in the unadjusted (mean government = 0.612, mean private = 0.784) and controlled analyses (mean government = 0.692, mean private = 0.789). The Hawaii State Department of Land and Natural Resources (DNLR)––the largest landowner with the largest percentage of FM cover in 2009––and the Department of Hawaiian Homelands (DHHL) had the lowest rates of decrease in FM cover (controlled mean DNLR = 0.663, controlled mean DHHL = 0.691). Mean decreases were greatest on state Office of Hawaiian Affairs (OHA) lands as well as lands owned by large private landowners (e.g., private utility company) (Table 2). These landowners, particularly OHA, had relatively lower FM cover in 2009 (Table 2). Lands with homeowner exemption and lands with a building present also had higher relative mean decreases in FM cover (Table 2). Mean decreases were low on lands with low building values (indicator of landowner wealth) and large properties (Table 3). Across land-use types, mean decreases in FM cover were greatest on lands with high-intensity development and lowest on agricultural land (Table 4). The majority (90%) of decreases were within 680 m of a road.

Preventative Management

Rates of FM decrease were 37 times greater than rates of increase. There was a 2.05% net increase in FM from 2009 to 2016 in areas that did not have FM in 2009 (0.29% annual net increase and 156.65 ha of increase). Mean rates of FM cover increase did not vary as much as rates of decrease by land ownership and land use; controlled mean rates of increase ranged from 1.2% to 3.6% across all land-ownership and land-use types (Table 2) (unadjusted were similar [Supporting Information]), except on OHA, private-corporation, and private-

Table 2. Mean probability of *Falcataria moluccana* (FM) decrease and increase* between 2009 and 2016 by land ownership variables controlled for elevation, wind, cloud, and distance to road.

10 landowners with largest area in study region	*Study area (%)*	*2009 FM cover on property (%)*	*Mean decrease on landowner property*	*Mean decrease on all other properties*	*Mean increase on landowner property*	*Mean increase on all other properties*
State-DLNR	17.854	16.531	0.663	0.786	0.023	0.022
State Office of Hawaiian Affairs	14.609	0.005	1.000	0.752	<0.001	0.022
Private educational trust	6.370	6.086	0.806	0.749	0.024	0.021
Private landowner (individual)	4.376	1.990	0.809	0.747	0.019	0.023
Private development company	2.330	1.987	0.920	0.747	0.016	0.022
State Department of Hawaiian Homelands	2.146	2.343	0.691	0.750	0.028	0.022
Private landowner, religious organization	1.157	4.731	0.703	0.756	0.036	0.022
Private corporation	0.726	0.580	0.959	0.751	0.004	0.022
County	0.313	0.717	0.791	0.751	0.012	0.022
Private utility company	0.015	0.057	0.972	0.751	0.004	0.022
Additional land ownership variables						
building present	21.854	24.831	0.827	0.731	0.019	0.025
homeowner exemption	7.633	6.181	0.855	0.746	0.020	0.022

**Decrease, number of cells with a decrease/total number of cells with FM in 2009; increase, number of cells with an increase/total number of cells without FM in 2009.*

Table 3. Mean probability of *Falcataria moluccana* (FM) increase and decrease per cell* from 2009 to 2016 by property size and building value controlled for elevation, wind, cloud, distance to 2009 FM (for decrease) and distance to road.

	1st quartile of property size or building value	*2nd quartile of property size or building value*	*3rd quartile of property size or building value*	*4th quartile of property size or building value*
Decrease				
property size	0.780	0.802	0.788	0.686
building value	0.664	0.779	0.808	0.827
Increase				
property size	0.023	0.020	0.025	0.012
building value	0.026	0.020	0.024	0.018

**Number of cells/total number of cells.*

Table 4. Controlled mean probability of *Falcataria moluccana* (FM) decrease and increase per cell from 2009 to 2016 by land-use variable.

	Study area (%)	*2009 FM in area (%)*	*Mean for land-use type*	*Mean not for land-use type*
Increase				
agriculture	8.709	10.450	0.029	0.022
high development	0.628	0.389	0.016	0.022
low development	8.841	8.195	0.018	0.023
Decrease				
agriculture	8.709	10.450	0.775	0.750
high development	0.628	0.389	0.835	0.751
low development	8.841	8.195	0.812	0.747

utility owned lands, where FM cover was relatively low in 2009 (Table 2). On these lands, controlled mean rates of increase ranged from <0.10% to 0.40% (Table 2). The mean rate of FM increase was slightly greater on private lands than government-owned lands in the unadjusted (mean government = 0.018, mean private = 0.022) and controlled analyses (mean government = 0.019, mean private = 0.023). Mean FM increase was slightly lower on large properties (Table 3) and in areas with high-building-value properties (Table 3). Increases were slightly lower in high-intensity property developments (Table 4). The majority (90%) of FM increases were within 200 m of an FM tree, within 788 m of a road, and at lower elevations (<242 m). Mean rates of increase were relatively consistent across soil ages (mean increase for soils 0–200 years = 0.02, 200–750 years = 0.023, 750–1500 years = 0.022, 1500–3000 years = 0.006, 5000–10,000 years = 0.021).

Discussion

We explored the utility of using spatially explicit, time-dependent analyses to examine the socioecological factors associated with conservation outcomes in human-dominated landscapes.

Case Study of FM Invasion

Previous studies link species distributions in human-dominated landscapes to characteristics of landowners and communities, such as absenteeism, landowner wealth, presence of a homeowner's association, public versus private ownership, and ecological and environmental factors (Hope et al. 2003; Kinzig et al. 2005; Gulezian & Nyberg 2010; Decker et al. 2012; Lerman et al. 2012; Niemiec et al. 2018). Although these studies provide insight into the socioecological factors associated with conservation outcomes, it is difficult to determine the processes by which social factors influenced outcomes. In the case of FM invasion in Hawaii, our spatially explicit, time-dependent analyses suggest that transformative management (i.e., controlling existing invasions), rather than preventative management (i.e., preventing establishment of new invaders), may have led to many of the observed associations between landownership characteristics and invasion.

Falcataria moluccana canopy decrease over 7 years varied substantially (66–100%) by land ownership. Although some percentage of the observed decreases was likely due to FM die-off from natural causes (covered above), these causes were likely driven by climatic and environmental variables, many of which we controlled for. It is possible that some unaccounted-for climatic and environmental drivers of natural die-off are associated with landownership variables, although we believe this unlikely given the selected range of variables. Thus, the large variation in decreases by landownership variables suggests that certain types of landowners are likely engaging in transformative action to control existing invasive species.

Mean rate of increase in invader cover varied only slightly by most landownership and land-use classes

(<0.1–3.6%). There are 3 primary explanations for a lack of variation in increase. First, invader spread and establishment could be reduced by landowner preventative action, but few landowners engaged in such preventative management efforts. Second, invader spread and establishment occurred independent of human action, so landowners could not effectively engage in preventative management even if they tried. Third, all landowners were equally engaging in effective preventative management efforts throughout their property. Although FM often spreads on its own through wind dispersal, FM seeds often establish in degraded soils that have been disturbed by humans (Hughes & Denslow 2005). Thus, while landowners may not be able to prevent seeds from spreading, they could potentially help prevent the establishment of FM by reducing disturbance and pulling saplings. We therefore believe the second explanation is unlikely. Furthermore, given the study area includes a mosaic of public and private landownership with different incentives and capacity (Niemiec et al. 2016), we believe the third explanation is much less plausible than the first.

If the first explanation is correct, then while certain types of landowners are engaging in transformative management actions to remove FM, these same landowners may not be engaging in effective preventative actions to stop increases of FM. This landowner focus on transformative management to control existing FM may have occurred in response to the damage caused by FM when Tropical Storm Iselle affected the Puna District in 2014. The storm caused thousands of FM trees to fall on homes, roads, and powerlines, stranding many residents in their homes for days. Many landowners responded by controlling, to the extent possible, the large FM trees on their properties and in their neighborhoods that posed an immediate threat to infrastructure (Niemiec et al. 2017). The combination of damage from Iselle and landowner management in response to this damage likely led to the high rates of FM decrease in the study area. However, although landowners may have been motivated after Iselle to control the FM trees that threatened infrastructure, it is possible they may not have been motivated to take concurrent preventative management actions.

If this were the case, an increased focus on motivating landowner engagement in preventative management to stop the spread and establishment of invasive species may be needed in forthcoming policy and outreach activities in Hawaii. Act 13 (Senate Bill 464) allows landowners to remove "nuisance" FM trees on neighboring private lands that pose a hazard to human safety after consulting an arborist and making reasonable attempts to contact the property owner. Current regulations facilitate management only if neighboring landowners contact the property owner and do not incentivize limiting disturbance, planting native species, or engaging in other actions to prevent the establishment of invasive non-native species.

Canopy cover decreases were more likely to occur on properties of landowners with more capacity or incentive to engage in control efforts. For example, there were substantial decreases in FM cover on land owned by a private utility company, which has a financial incentive to control the tree due to its tendency to fall on powerlines in high winds. Decreases were greater on lands with homeowner tax exemption. This was perhaps because homeowners living on their property have a financial and personal incentive to protect their property from damage caused by FM. Decreases were greater on lands with a building, possibly because absentee landowners who have no buildings on their property have no incentive to control FM. Decreases were also greater on lands owned by large private corporations and on lands containing high-value buildings. These landowners may be more prone to control existing FM because they can afford removal. Removing a single FM tree in close proximity to infrastructure requires a professional, which can cost \$2000–\$10,000 per tree (F. Brewer, personal communication). Thus, FM management may present an environmental justice issue.

Our results therefore suggest the need for outreach programs and policies that can help low-income landowners and others we identified with low capacity and incentives engage in transformative management to reduce existing FM populations. A static, cross-sectional analysis linking invasion to low-income landowners (e.g., Niemiec et al. 2018) would not be able to facilitate such a specific recommendation. This is because in a static analysis, observed correlations between low-income landowners and invasion could be the result of low-income landowners being more likely to introduce invasive species; less likely to engage in landscaping practices to prevent the establishment of invaders; or less likely to engage in control of existing invasive species that are already widespread. Our case study demonstrates how longitudinal analysis can rule out the former 2 explanations in favor of the latter, thus providing managers with a specific set of behaviors they can target for these populations.

A key limitation to our approach is that we used landownership data from 1 year (2013) in the middle of our study period. We therefore assumed that landownership characteristics recorded in 2013 were consistent throughout the study period. In reality, some characteristics, such as homeowner exemption, may have changed over time. Future studies are needed that link changes in social factors with changes in species distributions over time.

Research Agenda for Using Spatially Explicit Time-Dependent Analysis

We argue that spatially explicit, time-dependent analysis can inform the development of more effective conservation plans by revealing the types of behaviors (preventative vs. transformative) that should be promoted through outreach programs for different types of landowners. In addition to examining the socioecological factors associated with invasive species distributions, our approach could be adapted to examine the factors associated with native species distributions and other biodiversity conservation outcomes (Table 1). For example, spatially explicit, time-dependent analysis could reveal the mechanisms underlying the previously observed link between the presence of homeowner associations and increased bird and plant diversity (Lerman et al. 2012). The observed correlation could be due to homeowner associations facilitating preventative management by limiting the extent of development on a property or across a community. Alternatively, such a correlation could be due to homeowner associations providing incentives or assistance to landowners seeking to engage in transformative management. As more studies adopt spatially explicit, time-dependent analyses, the conservation community may gain insight into whether there are broader trends in how different social factors (e.g., income, homeownership, community social capital, and property size) influence transformative versus preventative management.

Obtaining spatially and temporally explicit data on conservation outcomes is increasingly possible through advances in remote sensing (Asner et al. 2012) and large-scale citizen science projects (Silvertown 2009). We suggest that linking such data to social factors, such as landownership, is a promising pathway forward for conservation research and policy. From a theoretical perspective, such analyses can clarify the mechanisms by which social factors influence conservation outcomes. From an applied perspective, such analyses can help direct managers toward the types of behaviors that should be promoted and thus the types of outreach programs and policies that may be needed for different landowner groups.

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Supporting Information

Additional methods (Appendix S1), unadjusted analyses (Appendix S2), and additional literature cited (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding authors.

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