Assessing Land Cover Dynamics and Evaluating Potential Management Implications of Gorse on Mauna Kea, Hawaii

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NREM 696 - Spring 2020
Master's MEM Capstone

Abstract

In Hawaii, invasive species have been declared “the single greatest threat to Hawaii’s economy, natural environment and to the health and lifestyle of Hawaii’s people” by the Hawaii State Legislature. On the Big island of Hawaii, a severe infestation of gorse (*Ulex europaeus),* occurs in the critical watersheds above Hilo. Decades of work has gone into containment and direct treatment; however, it’s still spreading. This study aims to better understand the environmental drivers of gorse expansion on Mauna Kea to inform management. I aimed to fill this gap by analyzing how distance to invaded areas, vegetative cover, fire disturbance, and annual rainfall variability might influence patterns of gorse establishment and spread. Density and probability plots were created to observe annual transitions across the range of each predictor. My results showed that under drier conditions there is a clear increase in the probability of gorse establishment, areas where bare earth cover was low but herbaceous cover was high resulted in the lowest probability of gorse establishment, and the highest density and probability of gorse establishment occurs near other invaded areas. Lastly, a Pearson’s chi-square test indicated fire promotes gorse establishment. I concluded that, the predictors used in this study do impact the spread and establishment of gorse over time. Furthermore, the data I’ve collected here can be used to develop predictive models of gorse spread into the future.

Introduction

Human activities, particularity trade, have resulted in plants and animals being transported all over the world, well beyond their range of natural distributions (Ziska & Dukes 2014). Although most species die in transit or soon after release, those that survive can become invasive and have serious impacts on human health, the economy, and the environment (Kolar & Lodge 2001). Plant species that are considered invasive typically possess traits or characteristics that aid in their ability to become invasive (Sakai et al. 2001). These traits include high seed production and viability, strong dispersal vectors, high reproductive potential, rapid growth rates, predator avoidance/deterrence, and a wide habitat tolerance (Wenning 2014; Sakai et al. 2001). Invasive species are causing dramatic changes in many ecological systems worldwide and are responsible for severely altering many native communities and ecosystems (Gurevitch & Padilla 2004; *Introduction to Invasive Alien Species* 2005).

The geographic isolation and volcanic origin of Hawaii has resulted in the islands being home to many unique ecosystems housing diverse plant and animal species, a large proportion of which are endemic to the islands (Keppel et al. 2014). Negative impacts of invasive species on native ecosystems of tend to be greater on islands because evolution isolated from mainland predators and disease has left the island species ill equipped to handle competition with the introduced species (Simberloff 1995). As a result, invasive species have been declared “the single greatest threat to Hawaii’s economy, natural environment and to the health and lifestyle of Hawaii’s people” by the Hawaii State Legislature (Hawaii Invasive Species Council 2015).

Gorse, (*Ulex europaeus*) a woody legume native to Western Europe and the Coastal Mediterranean, was first introduced to Hawaii in 1910 as a food plant for sheep and a living-fence for containing livestock (Zouhar 2005). Now, severe infestations have reached high-elevation agriculture and conservation lands on both the islands of Maui and Hawaii (Leary et al. 2005; Motooka et al. 2003). The species is a thorny shrub with bright yellow flowers that has multiple trait advantages which have allowed it to become invasive in Hawaii. The invasive nature of gorse has been attributed to the dense impenetrable thickets that outcompete other vegetation, long-term perennial growth, its ability to fix nitrogen, and a large and persistent soil seed bank that produces up to 14 million seeds per acre per year and persists in the soil for up to 50 years (Global Invasive Species Database 2019; Leary et al. 2005; Motooka et al. 2003).

The Big island of Hawaii is home to Mauna Kea, a dormant volcano with a peak 4,207m above sea level. The land use history of Mauna Kea has included logging, conversion to pasture, and intense cattle grazing, which has rendered the landscape vulnerable to invasion and infestation by invasive species (Convention on Biological Diversity n.d; Scowcroft & Conrad 1992). The subalpine ecosystem of Mauna Kea occurs between 2000m and 2850m elevation and historically consisted of two distinct woodland types: Mamane and Naio (Scowcroft & Conrad 1992). Mauna Kea supports the best remaining example of this habitat type. The dry, high elevation forest, currently heavily degraded from historical deforestation for grazing and current wild ungulate populations, is primarily covered by non-native pasture grasses and the non-native invasive species gorse (Kimball 2016).

Figure 1. A satellite image from Google Earth on 5/1/20 depicting the location of the core gorse population on Mauna Kea.

On Mauna Kea, the majority of the gorse infestation occurs in the high-elevation watersheds above Hilo, which were set aside in 1921 as a land trust for homesteading by native Hawaiians to maintain traditional ties to the land (Figure 1) (`Āina Mauna Legacy Program 2009; Scowcroft & Conrad 1992; Bateman & Vitousek 2018). This habitat, a public hunting and game reserve area is biologically and culturally important for several endangered or threatened native bird species. Gorse is severely limiting watershed managers (Mauna Kea Watershed Alliance and the Department of Hawaiian Home Lands) ability to restore environmental, economic, social, and cultural benefits to the trust lands. The current estimated extent of the 'core' area – seen in Figure 1 is about 15,000 acres. The gorse infestation is directly adjacent to the Hakalau Forest National Wildlife Refuge and threatens to compete with the native and endangered species in the protected high-canopy forest habitat (Leary et al. 2005). Decades of work has gone into containment and direct treatment of gorse, but it is still spreading. The ability to restore, protect, and conserve the watersheds for future generations heavily depends on effective gorse management.

The purpose of this study is to better understand the environmental drivers of gorse expansion to better inform management. If management aims to slow down (or stop) the spread of gorse, identifying potential drivers of gorse establishment, and how they influence spread, are crucial for management success. This study will specifically examine the effects of annual rainfall variability, fire, and ecosystem heterogeneity on the probability of gorse establishment within the 'core' gorse population area on the upper slopes of windward Mauna Kea described above.

Understanding gorse expansion in response to rainfall variability has important implications for ecological change due to shifting rainfall patterns anticipated with climate change (Lauer et al., 2013). Annual rainfall variation also might influence species interactions. In particular, the dynamics between invasive grasses on Mauna Kea and opportunities for the establishment of gorse. A key concern of land managers working to contain gorse is that drought results in grass die-back, and they are unsure how this may affect gorse establishment. A previous study on native and exotic plant species found significant variation response to variations in rainfall quantity, which makes it difficult to predict how certain species will respond (Ashbacher & Cleland 2015). Establishing a relationship between rainfall and gorse expansion could be used to predict how the population will respond to both current and future changes in rainfall availability.

Managers are also concerned about fire and gorse expansion. Two large fires occurred within the core area in 2002 and 2008, and are anecdotally associated with increased gorse establishment. Controlled burning is an effective tool to thin gorse thickets and reduce the seed bank (Marino et al., 2011). However, gorse is also well adapted to fire, therefore unplanned wildfires carried by the nonnative grasses may also provide opportunities for this species to increase in extent. A study experimenting with fire in Mediterranean gorse shrublands found small differences in vegetation composition can cause large differences in fire behavior that can affect vegetation regeneration (De Luis et al. 2005). These interactions are complex, but few studies have looked at how these phenomena interact together.

The propagation of gorse is also influenced by habitat dynamics and environmental heterogeneity (Cordero et al. 2016). Patterns of spread may be linked to the heterogeneity of the landscape prior to gorse establishment (León et al. 2016). I intend to examine heterogeneity by looking at the spatial distribution of gorse ‘sources’ or gorse occupied spaces in the landscape, as well as how the variability in vegetative cover influences the ability of gorse to establish. Understanding how these dynamics can influence the pattern of spread as well as how variations in vegetative cover limit or provide opportunities for establishment can provide important insights into landscape distribution and the probability of habitat invasibility.

Objective

Given the need for effective gorse management on Mauna Kea in light of the many agency and community reports (e.g. Maunakea Invasive Species Management Plan & Maunakea Plant Threats, Identification, Collection & Processing Guide by the Office of Maunakea Management, and Report of the Hui Hoʻolohe by EnVision Maunakea) indicating the high priority of gorse control, my objective is to assess the dynamics of gorse expansion over time in response to precipitation, disturbance, and habitat heterogeneity, and use these to inform managers and point to future analysis for predicting gorse expansion. This project used a novel remote sensing tool to determine gorse expansion on annual time steps and thereby attribute gorse spread and establishment to the following ecological conditions: (1) distance to invaded areas; (2) habitat heterogeneity in terms of vegetative cover; (3) fire disturbance ; (4) annual rainfall variability.

Methods

Study area

This study focused on the core gorse population of Mauna Kea owned by the Department of Hawaiian Home Lands (`Āina Mauna Legacy Program 2009). The gorse study area was selected to constrain the analysis to Heather Kimball's known gorse distribution in 2015 within the grassland areas, which makes up the 'core population' (Figure 2) (Kimball, 2016). I used Hawaii Fractional Land Cover Series (HFLCS) which provides annual, high resolution, percent cover maps of woody vegetation, herbaceous vegetation, and bare earth in Hawaii from 1999 to 2016 (Lucas et al., 2018) to determine gorse establishment on annual time steps. I limited my study area to the 'core' area within the nonnative grasslands because, given the three classifications available from the HFLCS, it is not possible to detect gorse invasion into forested areas already dominated by woody vegetation.

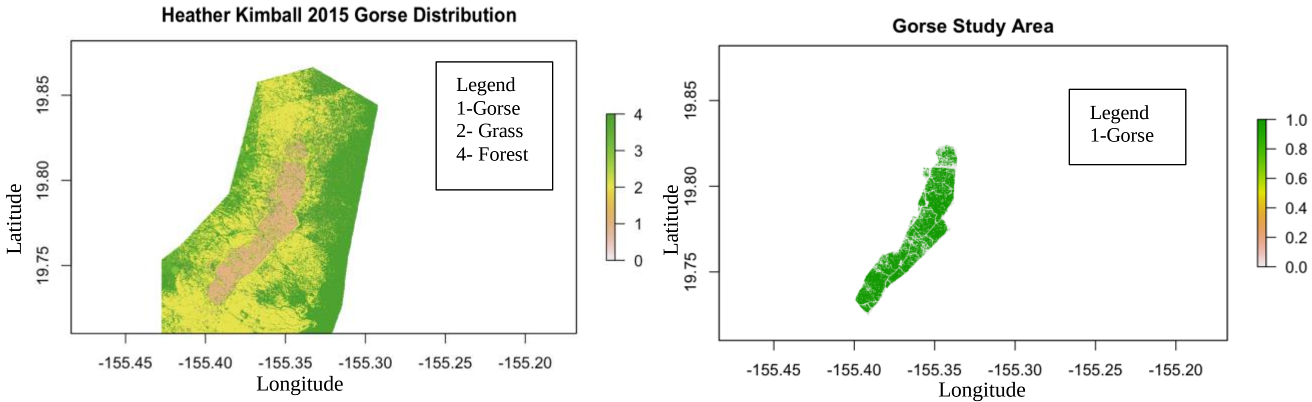


Figure 2. On the left: results of high-resolution supervised land cover classification of gorse from 2015, taken from Kimball, H. (2016). On the right: the selected study area, including Heather's 2015 data re-projected to match HFLCS extent and resolution.

Explanatory variables of gorse expansion

I used Kimball's (2015) high resolution gorse distribution map from 2015 to validate and establish gorse classification within HFLCS. Gorse is classified as woody vegetation within HFLCS, so I took the 2015 HFLCS and looked at the distribution of percent woody cover values for all the known gorse pixels in the core area confirmed as gorse by Kimball (2015). This provided a threshold in percent woody cover above which I could confidently identify 'gorse-occupied pixels' from the HFLCS. I used this threshold to establish a baseline of gorse-occupied pixels from the 1999 HFLCS.

To determine gorse transitions on annual time steps, I established a gorse transition ruleset in which a change from a non-gorse pixel to gorse only occurs if the change in percent woody cover from one year to the next is greater than 40%. This threshold in annual change was used to account for HFLCS having a root mean square error of about 20% (Lucas et al., 2018). This ruleset let me determine which pixels transitioned to gorse each year from the ones that didn't, which I could then use to track the invasion over time.

This allowed me to look at the probability of gorse establishment across all years by comparing all pixels that transitioned each year to gorse with the pixels that did not. Characterizing annual pixel transitions from 1999-2012, then allowed me to examine the effects of annual rainfall, fire disturbance, distance to nearest gorse patch, and vegetative cover on the probability that an unoccupied pixel became occupied by gorse, or the gorse transition probability.

For the purposes of this study, I examined the individual effects of the predictors on the gorse transition probability to examine potential relationships and inform managers. The response variable of 'annual gorse establishment' allowed me to look at the probability of pixels in the landscape becoming gorse at time T+1 based on conditions of the predictors at time T. By linking the annual conditions to the transitions, I can see what might have influenced whether a pixel transitioned to gorse or not.

Annual rainfall anomaly was derived from historical monthly rainfall grids by calculating the difference between annual rainfall and mean annual rainfall (Frazier et al., 2016). Two fires occurred in the area– so I looked at whether an area burned or did not burn, to see whether the transition occurred in the absence of or after a fire. I converted prior years gorse rasters to a spatialPointsDataFrame from which I could calculate the distance between pixels and the previous year's gorse locations. Lastly, I took herbaceous and bare earth cover values for each year. So, for every year for every for every pixel transition I had the prior year's environmental conditions.

I looked at these transitions in 2 ways. First, I first compared the distribution of each predictor at time T for the two types of annual observed transitions (either pixels were not gorse and became gorse, or pixels were not gorse and remined not gorse) by creating density plots for the annual observed transitions across the range of each predictor. I then examined how the probability of gorse establishment changes over the range of each predictor. This was done by grouping all the observed transitions and plotting the proportion of pixels invaded by gorse at time T+1 across binned values of each predictor at time T.

This allowed me to explain how rainfall, existing non-gorse cover, and distance to invaded areas influence the spread. The fire occurrence data was categorically classified as burned or not burned which would allow for a contingency table analysis. Pearson's chi-squared test with Yates' continuity correction was done to determine if fire and gorse establishment are independent.

Results

The amount of gorse establishment varied between years within the study area. The species had the largest amount of establishment from 2001-2002 and 2003-2004 with 17,817 pixels becoming gorse (Table 1). 2000-2001 had the lowest establishment numbers with no new gorse pixels detected (Table 1).

Gorse invaded pixels had a higher density in drought years compared to pixels that were not invaded. This shows a greater number of pixels transitioned to gorse during drought years than non-drought years (Fig. 3). Accordingly, with a lower rainfall anomaly gorse tends to exhibit a higher probability of establishment (Fig. 3). Most of the observations of annual rainfall fell between -500 and 500mm annual rainfall anomaly, with some observations falling under extremely dry conditions, and a lack of observations under extreme wet years. There is a clear increase in the probability of gorse establishment under drier conditions, and under extreme drought there is overall higher probability but it's also more variable.

Comparing the distributions of bare earth cover between invaded and non-invaded pixels show that invaded pixels tend to be distributed over a wider range of values for bare earth cover (Fig. 4). Non-invaded pixels tend to be concentrated where bare earth cover is low (Fig. 4). This implies that those non-invaded pixels are occupied by some kind of cover, most likely grass. A similar pattern is illustrated in the probability plots in which you can see a peak in the probability of gorse establishment around proportional bare earth cover of about 10%, while high proportions of bare earth (60%+) have a much lower probability of gorse establishment (Fig. 4).

For herbaceous (grass) cover, the bulk of non-invaded pixels had higher values of herbaceous cover (Fig. 5). In contrast, invaded pixels were spread more evenly across the distribution of herbaceous cover, with a peak around 60% herbaceous cover (Fig. 5). This aligns well with the probability of gorse transition being highest between 40-60% herbaceous cover and having low probability at the highest percentages of herbaceous cover (Fig. 5).

Looking at distance results, there was a strong effect of distance to invaded pixels on gorse establishment. The vast majority of gorse pixels were found to be 30-50m away from the nearest invaded pixel (Fig. 6). The 30x30m pixel size used in the study indicates that the majority of pixels that became gorse established directly next to other pixels that were already invaded with gorse. The probability plots reiterate this fact that the highest probability of gorse establishment is next to existing gorse and the probability decreases as the distance to gorse increases (Fig. 6).

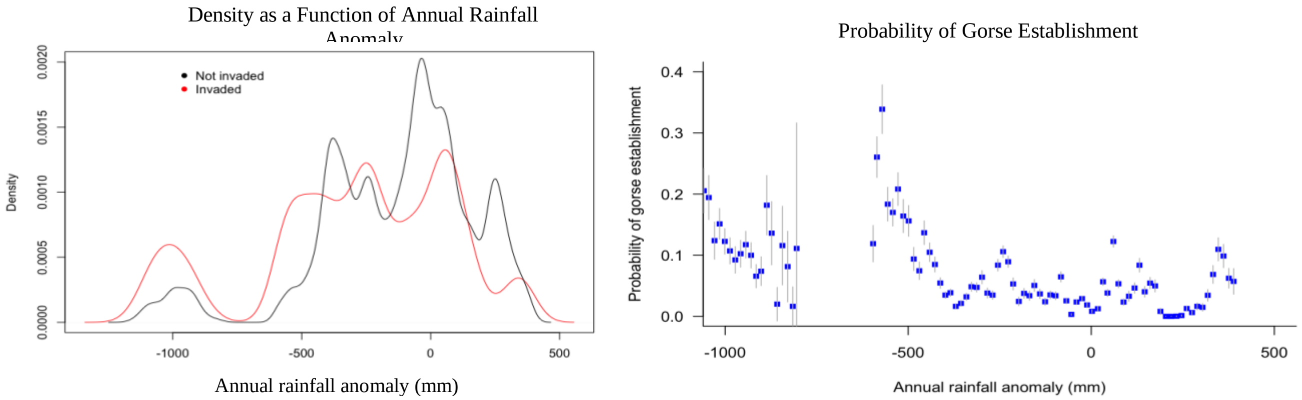
The Pearson's chi-square test for fire and gorse establishment had a p value smaller than .005 so this indicated that a greater proportion of burned pixels transitioned to gorse than would be expected at random, indicating fire promotes gorse establishment. The occurrence of fire resulted in a significantly greater number of gorse-invaded pixels than pixels that weren't burned (Table 2).

Table 1. The total number of pixels in the study area that became gorse each year from 1990-2012. Note: Year 1999 was the earliest data, therefore 7,365 represents the total amount of gorse pixels at that time. The establishment prior to that year is unknown.

Year	**1999**	**1999-2000**	**2000-2001**	**2001-2002**	**2002-2003**	**2003-2004**	**2004-2005**	**2005-2006**	**2006-2007**	**2007-2008**	**2008-2009**	**2009-2010**	**2010-2011**	**2011-2012**
Number of Pixels that became Gorse	7365	17	0	17817	17817	17223	15741	15209	14342	12228	11890	11016	11016	9635

Table 2. The contingency table showing the number of pixel observations annually throughout the study that were either not gorse and did not burn over the scope of the study, was not gorse and did previously burn at some point over the scope of the study, was gorse and did not burn over the scope of the study, or was gorse and previously did burn at some point over the scope of the study. The Pearson's chi-square test resulted in a p-value of <2.2e-16 indicating that a greater proportion of burned pixels transitioned to gorse than would be expected at random, demonstrating fire promotes gorse establishment.

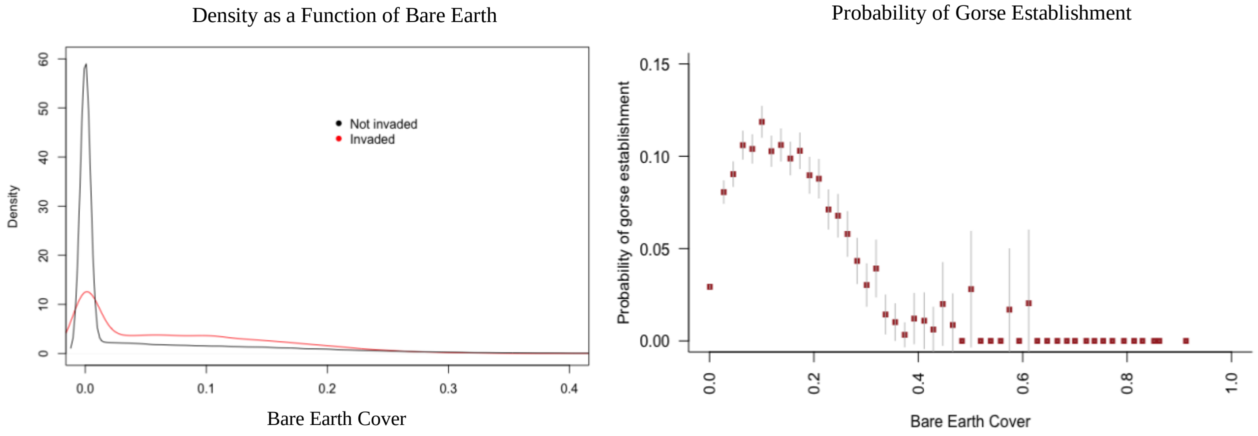
	0- not burned	1- burned
0 - not gorse	162161	17879
1- gorse	8106	1630



Density as a Function of Annual Rainfall Anomaly

Probability of Gorse Establishment

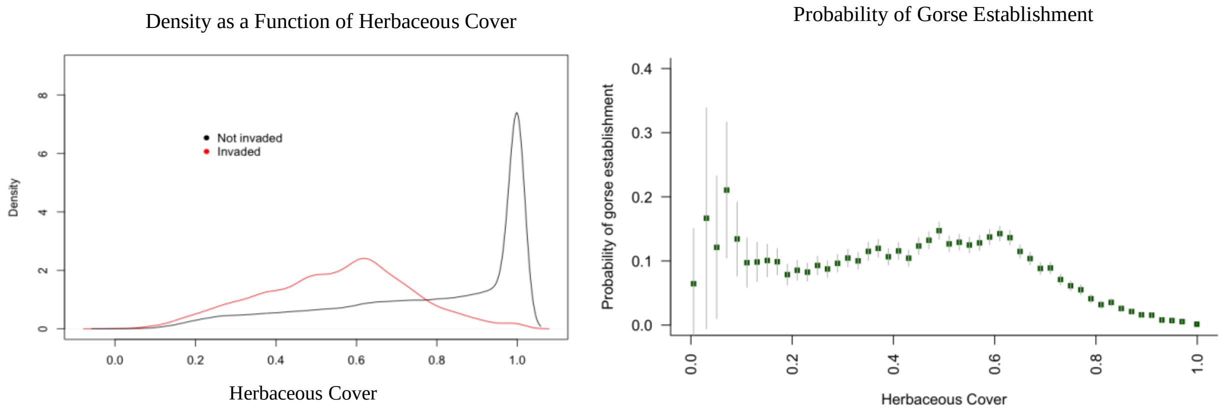
Figure 3. Graph on the left depicts density as a function of annual rainfall anomaly. Graph on the right shows the probability of gorse establishment based on annual rainfall anomaly.



Density as a Function of Bare Earth

Probability of Gorse Establishment

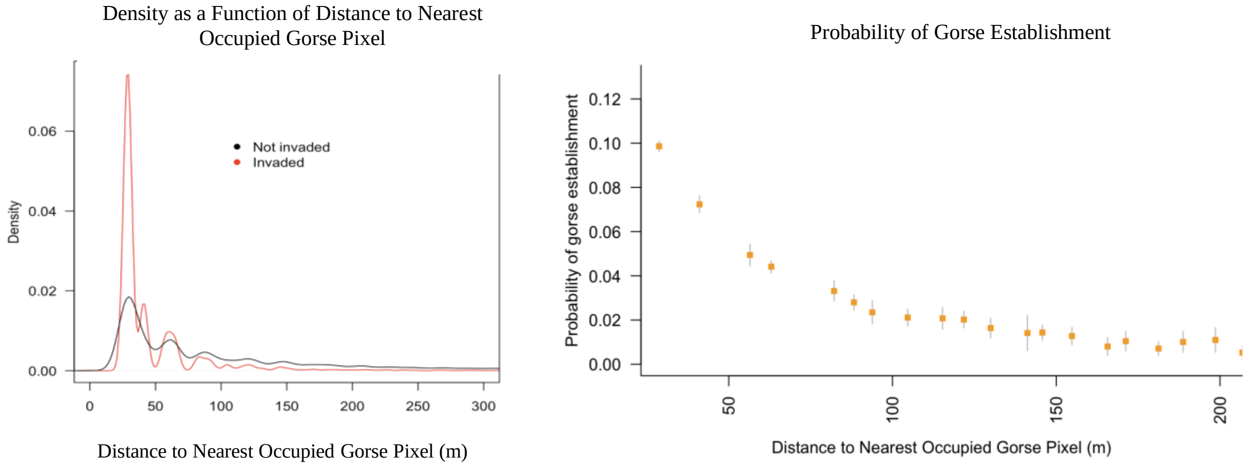
Figure 4. Graph on the left depicts density as a function of bare earth cover. Graph on the right shows the probability of gorse establishment based on the amount of bare earth cover.



Density as a Function of Herbaceous Cover

Probability of Gorse Establishment

Figure 5. Graph on the left depicts density as a function of herbaceous cover. Graph on the right shows the probability of gorse establishment based on the amount of herbaceous cover.



Density as a Function of Distance to Nearest Occupied Gorse Pixel

Probability of Gorse Establishment

Figure 6. Graph on the left shows the distance of invaded and not invaded pixels to the nearest invaded gorse pixel. Graph on the right shows the probability of gorse establishment based on the distance to the nearest invaded gorse pixel.

Discussion

This study provides evidence of the important role that rainfall variability and other landscape characteristics play in gorse establishment on Mauna Kea. Landscapes differ in the composition and configuration of habitats and distribution and quantity/cover of vegetation, and this heterogeneity also has an influence on the probability and spread of gorse.

Changes in amount of precipitation has been implicated in determining plant distributions across landscapes (Kosanic et al. 2018). The relationship between gorse establishment and annual rainfall variability presented here shows that gorse tends to benefit from dryer years and years of extreme drought. This is likely due to gorses' ability to outcompete grasses and native plants because of its association with nitrogen-fixing bacteria, which facilitate its establishment in poor soils (Magesan et al. 2012). The relationship between gorse establishment and annual rainfall variability presented here show that drought and grass die-back benefit gorse establishment. The grass-gorse-climate interactions show that managers need to be able to respond during drought with expanded treatment programs/effort. Climate change also threatens Hawaii's terrestrial ecosystems, with projected declines in rainfall (Chu et al. 2010). If precipitation change associated with future climate change results in an increase in dryer years or years of extreme drought, this will increase the probability of gorse establishment and likely the abundance of gorse.

The landscape of the study area on Mauna Kea is comprised mostly of a mix of invasive grasses, gorse, and bare area. My results allowed me to look at how these aspects vary over space and time and characterize/establish how they are actually heterogenous. The variability in vegetative cover this study investigated was between the percentages of woody, herbaceous, and bare earth. I examined how this spatial and temporal variation can affect the spread and establishment of gorse. It was found that non-invaded pixels tended to be concentrated where the percentage of bare earth cover was low, but grass cover was high. This indicates that non-invaded areas are likely to have high percentages of herbaceous cover, which coincides with the low probability of gorse establishment found in areas with high herbaceous cover. The results suggest high percentages of herbaceous cover can be a deterrent to gorse establishment likely by either impeding dispersal, or severely limiting the suitability for gorse survival. High percentages of bare earth also resulted in low probabilities of gorse establishment, suggesting those areas are unsuitable for plant establishment. Another study found that sparse non-natives despite exposed bare ground suggests physical limitations or abiotic factors are limiting non-native establishment in those areas (Averett et al. 2016), which is likely the case on Mauna Kea. Results show it is important to understand and be able to characterize heterogeneity to predict a given area's vulnerability to invasion.

Gorse grows quickly and produces large amounts of seeds. Pods burst and eject the seeds up to 5m, but mainly fall around the plant (Ulex Europaeus, USDA Forest Service). This corroborates the results that the highest density and probability of gorse establishment occurs near other invaded areas. The more distance from an invaded area the lower the probability of gorse establishment. Gorse dispersal among intermediate distances may be attributable to insects, animals, and possibly wind gusts or water transport (Ulex Europaeus, USDA Forest Service). It may seem intuitive, but this distance effect is important in that it supports the current strategy of containing the core area until control efforts can be scaled up.

Gorse is referred to as a "pyrophytic" (fire-loving) species in its native range (Foregard, 1990). Gorse has a high concentration of volatile oils, produces considerable biomass, is highly flammable, and burns rapidly with a high intensity (Ulex Europaeus, USDA Forest Service). In addition to removing competitors, literature shows fire promotes germination from the seed bank, allowing for post-fire regeneration (Dent et al. 2019). This relationship between gorse and fire on Mauna Kea as shown by Pearson's Chi-Squared test indicates that disturbance in non-invaded pixels increases the chance that they'll be invaded in the future. There was a significant association between whether an area burned or not and gorse establishment. This indicates that fire may be a tool to control existing gorse stands, but managers must be cautious and not let fires escape, because burned areas adjacent to gorse areas will be far more likely to become invaded.

Once established, gorse tends to dominate an area, evident of what is occurring on Mauna Kea. Based on the amount of annual establishment, it is clear that gorse control requires a long-term commitment. Clearly, fire exclusion from adjacent grasslands is critical, as well as being able to respond during drought with expanded treatment programs/effort. Finally, the results emphasize that the current containment strategy is likely necessary, as the invasion is most likely to spread adjacent to the core areas.

Continual monitoring of the distribution is important, and the information provided by this study can be used to prioritize management actions to particular areas of the landscape to achieve the most effective reductions in spread rate. As a next step, the fundamental relationships determined from this study can be integrated into more sophisticated predictive models to be able to run scenarios from the current situation moving forward into the future to predict out gorse establishment.

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