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January 30, 2013

Dr. Dan Binkley
Editor-in-Chief, *Forest Ecology and Management*

Dear Dr. Binkley:

Attached please find an original research paper for consideration for publication in *Forest Ecology and Management* (**Changes in land cover and fire behavior associated with nonnative grass invasion on a tropical island**) by L.M. Ellsworth, C.M. Litton, A.P. Dale, and T. Miura.

Throughout tropical ecosystems, it is accepted that nonnative grass invasion and repeated fires result in landscape scale conversion from forest to grassland, however existing research has been limited to an examination of these processes at the plot level. In this study we tested this dominant paradigm on a landscape scale in Hawaii. Specific objectives were to: (*i*) compare potential fire behavior in forests vs. grasslands, and (*ii*) measure land cover change from 1950-2011 along two grassland/forest ecotones in Hawaii. We found that potential fire behavior was 2-5 times more extreme in grasslands than in forests, and that rapid conversion from forest to grassland occurred for ~40 years prior to implementation of active fire management in the early 1990's. These results support general paradigms for the tropics, and demonstrate that type conversion associated with nonnative grass invasion and subsequent fire occurs widely on tropical islands without active management.

This work is original unpublished research, and no part of it has been or is being considered for publication elsewhere. We are willing to cover publication costs, including reproduction of color figures (submitted) if this paper is accepted for publication. We have suggested several potential reviewers (Dr. Jim Jacobi, Dr. Andrew Elmore, Dr. Lloyd Loope, and Ms. Anne Marie LaRosa), all of whom have extensive experience with issues of land cover change, invasive species, and fire ecology in the tropics. There are no conficts of interests among the authors of the submitted manuscript and these potential reviewers.

Thank you for your time and consideration, and please do not hesitate to contact me with any questions you may have.

Sincerely,

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Changes in land cover and fire behavior associated with nonnative grass invasion on a tropical island

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Abstract

It is generally accepted that the synergistic effects of nonnative grass invasion and subsequent fire result in landscape scale conversion from forest to grassland throughout the tropics. However, there is little published data to support this paradigm on a landscape scale on tropical islands, and no study has examined changes in fire potential following type conversion in these systems. If true, nonnative grasslands are more flammable than forests due to changes in fuel loads and microclimate and, thus, are at increased risk of fire occurrence and spread. Our objectives were to: (*i*) compare potential fire behavior in forests vs. grasslands, and (*ii*) measure land cover change from 1950-2011 along two grassland/forest ecotones in Hawaii. We quantified fuel loads and moistures in nonnative forest and grassland (*Megathyrsus maximus*) plots (n=6), and used these field data to model potential fire behavior using the BehavePlus fire modeling program. Rate and extent of land cover change were quantified from 1950-2011 with historical imagery. Live and dead fuel moisture content and fine fuel loads did not differ between forests and grasslands, but mean surface fuel height was 31% lower in forests (72 cm) than grasslands (105 cm; P<0.02). However, predicted fire behavior differed greatly in forests vs. grasslands. Rates of spread were 3-5 times higher in grasslands (5.0-36.3 m min-1) than forests (0-10.5 m min-1) (P<0.001), and flame lengths were 2-3 times higher in grasslands (2.8-10.0 m) than forests (0-4.3 m) (P<0.01). Between 1950 and 2011, invasive grassland cover increased in heavily utilized grassland areas at both Makua (320 ha) and Schofield (745 ha) at rates of 2.62 and 1.83 ha yr-1, respectively, with more rapid rates of conversion before active fire management practices were implemented in the early 1990’s. These results support accepted paradigms for the tropics, and demonstrate that the type conversion associated with nonnative grass invasion and subsequent fire has occurred on a landscape scale. Moreover, once forests were converted to grassland there was a significant increase in fire intensity, likely providing a positive feedback to continued grassland dominance in the absence of active fire management.

Keywords: BehavePlus, fire modeling, land cover change, guinea grass, *Megathyrsus maximus*

1. Introduction

It is generally well accepted that the synergistic effects of nonnative grass invasion and repeated wildfire in the tropics detrimentally impacts native species (Loope, 1998; Eva and Lambin, 2000; Hoffmann *et al*., 2002; Loope, 2004; Hughes and Denslow, 2005), and often converts woody plant communities into nonnative grasslands (Hughes *et al*., 1991; D'Antonio and Vitousek, 1992; Ainsworth and Kauffman, 2010). In Hawaii, as with other tropical island ecosystems, grass invasion and increased fire frequency is particularly problematic because fire is not believed to have played a historically large role in the evolution of these unique island ecosystems (LaRosa *et al*., 2008). As a result, many native species do not possess adaptations to survive a regime of frequent fires (Rowe, 1983; Vitousek, 1992) or to passively recover following fire (D'Antonio *et al*., 2011). While prior studies have examined grass-fire interactions on tropical islands at the plot level (Hughes *et al*., 1991; Ainsworth and Kauffman, 2010), no study has quantified type conversion to nonnative grasslands over large spatial extents or long temporal scales. One recent study in Hawaiian submontane forests showed that at the plot level, nonnative grasses remain dominant, with little native recovery, up to 37 years after fire and conversion of native forest to nonnative grassland (D'Antonio *et al*., 2011).

Invasive grasses in the tropics alter the occurrence and behavior of fires via a variety of both intrinsic (characteristics of the plants themselves) and extrinsic (arrangement of plants across the landscape) fuel properties (Brooks *et al*., 2004). Intrinsic fuel properties associated with type conversion from forest to grassland can include increased flammability due to lower fuel moisture (Brooks *et al.*, 2004) and competitive superiority in the postfire environment (Veldman and Putz, 2011). Extrinsic properties, in turn, can include increased horizontal fuel continuity (Brooks *et al.*, 2004), changes in microclimate (Blackmore and Vitousek, 2000; Hoffmann *et al*., 2002), increased fine fuel loads (Litton *et al*., 2006) , and change in fuel packing ratios (Brooks *et al*., 2004; Hoffmann *et al*., 2004).

Highly flammable African pasture grasses have been widely introduced throughout the tropics where they are now problematic invaders (D'Antonio and Vitousek, 1992; Williams and Baruch, 2000). In Hawaii, these grasses were introduced primarily for livestock forage and as ornamentals in the late 1800’s and early 1900’s (Williams and Baruch, 2000; Motooka *et al.*, 2003). In addition to impacting fire regimes, these invasive grasses commonly outcompete native plants for above- and belowground resources (Ammondt and Litton, 2012; Ammondt *et* *al.*, 2012), and alter carbon storage and forest structure (Litton *et al.*, 2006) and nutrient dynamics (Asner and Beatty, 1996; Mack *et al.*, 2001). These highly competitive grasses typically form a continuous layer of fine fuels, even under a forest canopy (LaRosa *et al.*, 2008), thereby increasing the potential for future fire and type conversion to nonnative grassland. Once a fire does inevitably occur, the postfire plant community is typically characterized by rapid nonnative grass regeneration, which then predisposes these ecosystems to more frequent and higher intensity fires as a result of increased fine fuel loads and changes in microclimate (Smith and Tunison, 1992; Pyne *et al.*, 1996; Blackmore and Vitousek, 2000; LaRosa *et al.*, 2008; Ainsworth and Kauffman, 2010). This cycle of nonnative grass invasion, fire, and grass reinvasion is a common occurrence in tropical ecosystems that leads to large scale land cover change (D'Antonio and Vitousek, 1992).

Throughout the tropics, conversion from forest to grassland has resulted in increased cover of invasive grasses (Williams and Baruch, 2000). Guinea grass (*Megathyrsus maximus*, [Jacq.] previously *Panicum maximum* and *Urochloa maxima* [Jacq.]), was introduced to Hawaii for cattle forage and became naturalized in the islands by 1871 (Motooka *et al.*, 2003; Portela *et al.*, 2009). As in other tropical ecosystems, guinea grass quickly became a problematic invader in Hawaiian landscapes because it is adapted to a wide range of ecosystems (*e.g.*, dry to mesic), where it alters flammability by dramatically increasing fuel loads and fuel continuity. Year-round high fine fuel loads with a dense layer of standing and fallen dead biomass maintain a significant fire risk throughout the year in guinea grass dominated ecosystems on tropical islands (Ellsworth et al, *in review*). Because guinea grass recovers quickly following disturbance (*i.e.* fire, ungulate grazing, land use change, etc.) and is competitively superior to native species (Ammondt & Litton, 2012), many areas of Hawaii, as well as throughout the tropics, are now dominated by this nonnative invasive grass (Ellsworth et al, *in review*).

Plot level studies provide important insights into the relationships between nonnative grass invasion, fire, and type conversion from forest to grassland, but a greater understanding of these dynamics is only possible by examining these processes at the landscape scale (Brook and Bowman, 2006; Levick and Rogers, 2011). Furthermore, an understanding the spatio-temporal dynamics of vegetation change over longer time scales can better elucidate the mechanisms driving vegetation change. Because the invasive grass–wildfire cycle has been so well documented at the plot scale, the dominant paradigm on tropical islands is that fire shifts composition from woody communities to nonnative grassland, that these changes persist over long time periods, and that the end result is a landscape that is increasingly dominated by nonnative invasive grasses that have a much higher fire risk than the forests that they replaced. However, few studies in the tropics have looked at landscape vegetation cover patterns resulting from repeated fire and grass invasion at larger scales (Blackmore and Vitousek, 2000; Grigulis *et al.*, 2005).

The objectives of this study were to: (*i*) use field data and modeling to compare fuels and potential fire behavior in adjacent forests vs. grasslands, and (*ii*) measure the rate and extent of land cover change at the grassland-forest boundary from 1950-2011 in and around two heavily utilized military installations on Oahu, Hawaii. We hypothesized that (*i*) fine fuel loads and heights would be lower and fuel moisture higher in forest plots than grass plots due to differences in understory microclimate (Hoffmann *et al.*, 2002) and shading (Funk and McDaniel, 2010) ; (*ii*) as a result of lower fuel heights and fuel loads, modeled fire behavior would be less severe (*i.e.* lower rates of spread, fireline intensity, flame lengths, and probability of ignition) in forest plots than grass plots (Freifelder *et al.*, 1998); and (*iii*) rates of conversion from forest to grassland would increase through time over the past 50+ years due to increased ignition sources, and rates of conversion would be higher in areas where there was already a large grass component than in adjacent forests (Beavers, 2001). To test these hypotheses, we quantified fuels in forest and grassland plots to model potential fire behavior, and quantified land cover change from 1950-2011 with historical imagery.

2. Methods

2.1 Fuel Quantification

Fuel loads in guinea grass-dominated open grassland (grass sites) and adjacent nonnative forest (forest sites) were quantified in the summer of 2008 in the Waianae Kai Forest Reserve (forest: 367 m a.s.l.; MAP [mean annual precipitation], 1399 mm; MAT [mean annual temperature], 20ºC) (grass: 193 m.a.s.l.; MAP, 1134 mm; MAT, 23ºC) and Dillingham Airfield (forest and grass: 4 m a.s.l.; MAP, 900 mm; MAT, 24ºC; T. Giambelluca, *unpub. data*) on the Waianae Coast and North Shore areas, respectively, on the Island of Oahu, Hawaii, U.S.A. (Figure 1). All sites are dominated by guinea grass in the understory. Forest sites at Waianae Kai Forest Reserve are dominated by nonnative trees, including *Leucaena leucocephala* (Lam.) De wit in the subcanopy and kiawe (*Prosopis pallida*) and silk oak (*Grevillea robusta*) in the overstory. Forest sites at Dillingham Airfield have dense nonnative *L. leucocephala* in the canopy, with infrequent other nonnative woody species scattered throughout. Soils at Dillingham Airfield are in the Lualualei series (fine, smectitic, isohyperthermic Typic Gypsitorrerts) formed in alluvium and colluvium from basalt and volcanic ash. Soils at Waianae Kai are in the Ewa series (fine, kaolinitic, isohyperthermic Aridic Haplustolls) formed in alluvium weathered from basaltic rock.

#Figure 1 approximately here#

Within each of the two sites, three grassland and three forest plots were selected using USGS imagery in Google Earth 5.0. Plot selection was based on continuous grass cover and limited overstory trees for grassland plots, and a continuous tree overstory with guinea grass in the understory for forest plots. Final plot selection was made randomly from all possible locations that met these criteria. In each site, the following fuel variables were measured: (*i*) total fuel loads (standing live and dead, and litter), (*ii*) fuel composition (live grass, dead grass, shrubs, standing trees, downed wood), (*iii*) mean fuel height (calculated as 70% of maximum observed surface fuel height in each plot (Burgan and Rothermel, 1984)) and (*iv*) live and dead fine fuel moisture. In each plot, three parallel 50m transects were established 25m apart, and all herbaceous fuel was destructively harvested in six 25 x 50 cm sub-plots at fixed locations along each transect (n=18/plot). This sampling design adequately captured the spatial variability in fuels at a given site (Ellsworth et al, *in review*). Samples were immediately placed into sealed plastic bags to retain moisture. Within 6 hours of field collection, all samples were separated into categories (live grass, standing dead grass, surface litter, and downed wood), weighed, dried in a forced air oven at 70^{o}C to a constant mass (minimum 48 hours), and reweighed to determine dry mass and moisture content relative to oven dry weight.

Live standing trees and standing and downed dead wood were also quantified in each forest plot. The diameter at breast height (dbh) of all *L. leucocephala* trees– the dominant species in all forest plots – in a single 1 x 50 m belt transects was measured in each forest plot. Live tree biomass was determined using an existing species-specific allometric equation for *L. leucocephala* (Dudley and Fownes, 1992). The utility of this allometry for estimating biomass in trees from the Waianae Kai field site was explored by harvesting trees across the widest possible range of sizes found (n=20, dbh ranging from 1.5 to 6.2 cm dbh) and comparing observed vs. predicted biomass. There was a strong correlation between predicted and observed biomass (r^2=

0.95), indicating that the existing equation accurately estimates *L. leucocephala* biomass in our study sites. While other woody species occurred in the general study area, none were encountered in any of the sampling transects. Coarse downed woody fuels were sampled along three 50 m transects/plot using a planar intercept technique (Van Wagner, 1968; Brown, 1974). In addition, the height of the tallest blade of grass was measured in each subplot before clipping, and mean fine fuel height was recorded as 70% of the average maximum height across subplots (Burgan and Rothermel, 1984).

2.2 Fire Modeling

The fuels data described above were used to parameterize the BehavePlus 5 Fire Modeling System (Andrews *et al.*, 2005) to predict fire behavior for each plot. Live and dead fuel heat contents were measured by bomb calorimetry (Hazen Research, Inc., Golden, CO, USA). Previously published values of dead fuel moisture of extinction for guinea grass (Beavers, 2001) and woody surface area to volume ratio for humid tropical grasslands (Scott and Burgan, 2005) were used. Surface area to volume ratios for both live and dead fuels were measured on guinea grass individuals from Dillingham Airfield and Waianae Kai Forest Reserve (*n*=20 overall using a LI-3100C Leaf Area Meter (LI-COR Environmental, Lincoln, Nebraska) and water displacement. After examining wind speed data collected at the field sites, we selected an average 20-foot windspeed (15 km hr-1) and an extreme 20-foot windspeed (30 km hr-1) to simulate moderate and severe wind scenarios that were then applied to all sites. Wind adjustment factors of 0.4 and 0.3 were used for grass and forest plots, respectively, to adjust the windspeed collected by the RAWS weather stations (20-foot wind speed) to that at the vegetation height (surface wind speed) (Andrews *et al.*, 2005). Output variables of interest from the fire behavior model included: maximum rate of spread (ROS; m min-1), fireline intensity (kW m-1), flame length (m), and probability of ignition (%).

2.3 Historical and Spatial Land Cover Change Analysis

Land cover classifications were made on orthorectified aerial photographs and high resolution multispectral Worldview-2 imagery for Makua Military Reservation (108 m.a.s.l.; MAP, 864 mm; MAT, 23ºC) and Schofield Barracks (297 m.a.s.l.; MAP, 1000 mm; MAT, 22ºC; (Giambelluca *et al.*, 2011); Figure 1). Classified maps for Makua were derived from images for five time periods: 1962, 1977, 1993, and 2004 aerial photographs, and 2010 Worldview-2 scenes. Schofield land cover maps were created for six time periods: 1950, 1962, 1977, 1992, and 2004 aerial photographs, and 2011 Worldview 2 scenes. The 2004 images for Makua and Schofield were high resolution (0.3 m) USGS registered images with a positional accuracy that did not exceed 2.12 m RMSE (root mean square error). The other images were registered to the 2004 images with a first-order polynomial warping (affine transformation) to achieve an average RMSE of 3.37 m and a maximum RMSE of 9.84 m. Worldview-2 images are high resolution (~0.5 m) with a positional accuracy of 12.2 m at the CE90 level.

Both Makua and Schofield site boundaries were digitized into polygon vector shapefiles using ArcGIS Desktop Version 9.3.1 (ESRI, Redlands, California, USA). Each site was divided into two areas of interest (AOI): a grassland area within the fire break which is heavily utilized for military training activities and a forested area outside the fire break, where little military activity occurs. While these areas were defined as grassland vs. forest, respectively, each contains patches of both grass and woody cover as well as patches of more intensive utilization (*i.e.* developed military training areas). The ArcGIS Data Management tool *Create Fishnet* was used to divide the study sites into grids with a 50 x 50 m cell size and clip the grids to the site boundaries. After the grids were created, they were overlaid onto the images for classification.

Each cell was classified into one of seven cover classes at Makua: Grass, shrub, forest, bare, developed, military training area (MTA; highly disturbed area with minimal vegetative cover), and shadow/cloud (treated as No Data). The woody plant composition at Schofield is highly variable and forest and shrub cover classes are often indistinguishable from aerial images. At Schofield, therefore, shrub and forest cover classes were combined into a single mixed woody cover class, resulting in only six cover classes for this site (grass, woody, bare ground, developed, MTA, and No Data). The total area of each cover class was calculated for every time period within the two AOIs for both sites. Amounts and rates of land cover change (expressed as average hectares per year) were then extrapolated for each of the four AOIs over each time period.

Examination of historical imagery showed an apparent pattern of increasing homogeneity over time. Therefore, we used Fragstats (McGarigal *et al.*, 2012), a spatial pattern analysis program, to quantify landscape metrics for each date at each AOI. Metrics examined included number of patches, contagion (the tendency of patches to occur in large, continuous patches; expressed as a percentage, where zero is maximum heterogeneity), and perimeter:area ratio.

2.4 Statistical Analyses

General linear models were used to determine whether there were differences in live and dead fine fuel loads, fine fuel moistures, average fuel height, fire behavior variables (ROS, fireline intensity, flame length) and probability of ignition between grassland and forest plots, after controlling for differences in mean annual precipitation (MAP) among sampled plots. Because there is an elevation/ precipitation gradient at Waianae Kai Forest Reserve, and forest plots were clustered ~150 m higher in elevation than grassland plots, MAP was included in the model to control for differences in environmental variables that may have potentially impacted fuels and fire behavior. Site was treated as a random factor, plot type (forest or grassland) was treated as a fixed factor, and MAP was used as a covariate. Live and dead fine fuel variables were log-transformed for analysis to meet model assumptions of normality and homogeneity of variance, but all results are presented herein as untransformed data. Minitab v. 15 (Minitab, Inc., State College, PA) was used for all statistical analyses, and significance was assessed at α=0.05. For Fragstats spatial analyses, AOI's within sites are not independent, and only two sites were analyzed, making statistical inference inappropriate. Therefore, this analysis was limited to an examination of temporal trends in patterns.

3. Results

3.1 Fuel Quantification

After controlling for differences in MAP (P<0.01), there were few differences in fine fuels between forest and grassland plots, with live fine fuels ranging from 2.1-5.9 Mg ha-1(P=0.86), and dead fine fuels ranging from 10.4-19.5 Mg ha-1 (P=0.89; Table 1). MAP was a strong predictor of both live (P=0.02) and dead (P=0.05) fuel moisture, and there was no evidence of differences in fuel moistures between forest and grassland (live, P=0.19; dead, P=0.95). Live fine fuel moisture at the time of sampling ranged from 47-173%, and dead fine fuel moisture from 14-65%. Mean fuel height, however, was 31% lower in forests (72 cm) than in grasslands (105 cm; P<0.02) after accounting for differences in MAP (Table1).

#Table 1 approximately here#

3.2 Fire Modeling

Despite holding microclimate constant and fuels only differing between forest and grassland in terms of height, predicted fire behavior differed greatly between these two land cover types (Table 2). Under moderate wind conditions (15 kph), rate of modeled fire spread was 3-5x higher in grassland (5.0-17.7 m min-1) than forest (0-5.0 m min-1) ($P<0.001$), and flame lengths were 2-3x higher in grassland (2.8-7.2 m) than forest (0-3.0 m; $P<0.01$). Fireline intensity at moderate wind conditions was also higher in grassland (2,426-19,034 kW m-1) than forest (0-2,914 kW m-1) ($P<0.01$). Under extreme wind conditions (30 kph), predicted rates of spread were 3-10x higher in grasslands (10.1-36.3 m min-1) than in forests (0-10.5 m min-1) ($P<0.001$); flame lengths were 2.5-4x higher in grasslands (3.9-10.0 m) than forests (0-4.3m) ($P<0.01$); and fireline intensity was higher in grasslands (4,919-39,004 kW m-1) than in forests (0-6,166 kW m-1) ($P<0.01$). Probability of ignition ranged from 0-32% and did not differ between cover types under either moderate or extreme wind conditions ($P=0.27$) (Table 2).

#Table 2 approximately here#

3.3 Historical and Spatial Land Cover Change Analysis

Invasive grassland cover increased in heavily utilized areas inside the firebreak at both Makua (total area of 320 ha) and Schofield (total area of 745 ha) at rates of 2.62 and 1.83 ha yr-1, respectively, over the entire 50+ years examined, with more rapid rates of conversion (up to 7.41 ha yr-1) occurring before aggressive fire management practices were implemented in the early 1990's (Table 3; Figures 2-5). At Makua, conversion from forest to grassland in the surrounding forest area (total area of 1244 ha) was slower (1.78 ha yr-1) than in the grass area (Figure 2). Unlike Makua, in the forest area at Schofield (total area of 1576 ha) conversion of grassland to forest occurred at a faster rate (4.75 ha yr-1) than in grass areas (Figure 3). Overall, change in land cover over time was more dynamic at Makua (Figure 3) than at Schofield (Figure 4), coinciding with large and frequent fires at Makua, and fewer acres burned at Schofield.

The number of patches decreased steadily in forest areas at both Schofield and Makua from 1950 until 1992/1993, and then increased again in 2004 and 2010/2011. The number of patches in grass areas fluctuated over time, without any clear trends (Figure 6a). Contagion in forested AOI's differed greatly by site. At Schofield, contagion was >50% for all dates, and reached >80% by 2004. At Makua, contagion also gradually increased, but remained much lower (29-49%) than that observed at Schofield. In the heavily utilized grass area, contagion was similar at both sites, ranging from 43-59%, and stayed fairly constant over time. The perimeter:area ratio varied greatly over the sample period, with no clear trends with treatment, time, or site (Figure 6c).

#Table 3 approximately here#

#Figures 2-6 approximately here#

4. Discussion

These results clearly show that the areas studied have experienced large type conversions from forest to grassland over the past 50+ years. This conversion to grasslands, in turn, altered fuel heights and increased modeled fire spread and intensity, which likely represents a positive feedback to grassland dominance (i.e., the invasive grass-wildfire cycle). As hypothesized, increased fuel bed depth and an increased effect of wind at the fuel surface (Freifelder *et al.*, 1998; Andrews *et al.*, 2005) in grassland has led to the potential for much more intense fire behavior compared to forest. These data support previous work in Hawaii (Hughes *et al.*, 1991; Freifelder *et al.*, 1998), and elsewhere in the tropics (Williams and Baruch, 2000; Hoffmann *et al.*, 2002; Rossiter *et al.*, 2003), demonstrating that, at the plot level, the synergistic effects of fire and nonnative grass invasion can lead to a pervasive invasive grass-wildfire cycle.

On a landscape scale, however, the interactions among fire, grass invasion, nonnative woody species and fire management appear to be much more complex. Because it is generally accepted that repeated fires and the presence of nonnative grasses lead to a landscape that is increasingly dominated by flammable grasslands, we expected to see an increase in the rate and extent of conversion in more recent years as compared to historical landscapes. While we acknowledge that the two valleys analyzed in this study do not mirror all landscapes in the tropics, they do represent among the most highly impacted end of the spectrum in terms of utilization intensity and opportunities for fire ignition (i.e., frequent military training activities). Because of this, we expected to see rapid rates of land cover conversion. The mean trend over time in grassland areas at both sites was a reduction in woody cover with a concomitant increase in grassland cover, as originally hypothesized. This was expected, as these areas are heavily utilized by military training activities, and ignitions from training are frequent. In the forests, however, there were different trends observed over time. At Makua, where fires have been larger and more frequent, the forest is slowly being replaced by grassland. Fire management has been exceedingly difficult at this site (Beavers *et al.*, 1999) due to low precipitation and fuel moisture, remoteness, intensity of military training, and common anthropogenic ignitions (*i.e.* arson, roadside). In 2004, all live fire training stopped at Makua to address fire concerns at this site, but several human ignited fires have since occurred.

At Schofield, however, the pattern of change over time in the forest was very different from Makua. Grass cover steadily decreased from 1950 to the present, while woody species, and to a lesser extent, military training areas, increased. While this area is inaccessible due to unexploded ordinance, we presume that most of the woody increase is due to the spread of nonnative woody species, rather than a recovery of a very limited native plant component in the area. Several factors may contribute to the differential response at Schofield. This site has ~16% higher precipitation than Makua (Giambelluca *et al.*, 2011), with higher fuel moistures (Ellsworth et al, *in review*). Additionally, fire managers at Schofield have been successful at containing fires within the fire break perimeter since improved fire management began in the 1990's. A well trained fire crew is housed on this instillation, and a well-designed fire management plan has largely limited severe wildfires (Beavers and Burgan, 2001).

From this study, it can be inferred that at a landscape scale, the grass-wildfire cycle may not be the final endpoint for all fire impacted and nonnative grass invaded tropical ecosystems, as is currently the paradigm in the science and management communities. A recent review of the impacts of woody invasive plants on fire regimes (Mandle *et al.*, 2011) showed that, while most discussion centers around the effects of grass invaders, invasive woody plants can also alter ecosystem properties and patterns, thereby impacting future fire regimes. A dominant nonnative woody invader in the forested area at Schofield, *Schinus terebinthifolius* Raddi (christmasberry) (Beavers and Burgan, 2001), may reduce fire temperature and spread (Beavers and Burgan, 2001; Stevens and Beckage, 2009), potentially offering an escape from the grass-wildfire cycle (Mandle *et al.*, 2011).

In summary, we investigated evidence for the dominant paradigm that grass invasion and subsequent fire lead to widespread conversion from forest to grassland and increased frequency and severity of wildfire on tropical islands. While these results show that grasslands are prone to more extreme fire behavior than forests, it was not always the case that increased flammability led to widespread increases in grassland cover across the landscape. In fact, many areas appear to be recovering a woody overstory, albeit nonnative, suggesting that active fire management is largely preventing further type conversion to nonnative grasslands.

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Table 1. Live and dead fine fuel loads (in Mg ha-1), fuel moisture (%), and maximum fuel height (cm) in open guinea grass ecosystems and forested ecosystems with a guinea grass understory on leeward Oahu, Hawaii. Means and standard errors are given for fuels variables at each site (*N*=3). Significant model factors are indicated by bold font in the last three columns.

Variable	**Dillingham Grass**	**Dillingham Forest**	**Waianae Kai Grass**	**Waianae Kai Forest**	**Model R^2 (%)**	**MAP**	**Site**	**Type**
							(P-value)	
live fine fuels	4.6 (0.9)	5.9 (3.9)	3.7 (0.4)	2.1 (1.0)	31.1	0.38	0.65	0.86
dead fine fuels	19.5 (4.3)	19.5 (3.0)	13.7 (0.6)	10.4 (1.8)	51.4	0.52	0.80	0.89
live fuel moisture	47.2 (3.6)	78.2 (13.1)	57.7 (9.0)	173.6 (27.3)	84.2	**0.02**	0.18	0.19
dead fuel moisture	13.6 (2.3)	23.4 (6.8)	15.5 (2.9)	65.2 (31.4)	61.7	**0.05**	0.14	0.95
max. fuel height	138.6 (9.7)	71.0 (3.0)	71.3 (10.7)	72.3 (12.0)	76.5	**0.02**	**<0.01**	**<0.01**

Table 2. Predicted fire behavior under both moderate (15 kph) and severe (30 kph) wind conditions in open guinea grass ecosystems and forested ecosystems with a guinea grass understory on leeward Oahu, Hawaii. Means and standard errors are given for fire behavior variables at each site (*N*=3). Significant model factors are indicated by bold font in the last three columns.

Variable	**Wind condition**	**Dillingham Grass**	**Dillingham Forest**	**Waianae Kai Grass**	**Waianae Kai Forest**	**Model R^2 (%)**	**MAP**	**Site**	**Type**
								(P-value)	
Rate of Spread	moderate	14.9 (1.6)	2.7 (1.2)	5.8 (0.6)	0.4 (0.4)	91.0	**0.04**	**<0.01**	**<0.001**
(m min -1)	severe	30.7 (3.1)	5.7 (2.6)	12.0 (1.2)	0.8 (0.8)	91.1	**0.04**	**<0.01**	**<0.001**
Flame Length	moderate	5.8 (1.0)	2.1 (0.5)	3.0 (0.2)	0.3 (0.3)	84.8	0.61	0.10	**<0.01**
(m)	severe	8.1 (1.4)	2.9 (0.8)	4.3 (0.3)	0.4 (0.4)	84.6	0.62	0.11	**<0.01**
Fireline Intensity	moderate	12829 (4075)	1503 (750)	2983 (537)	57.7 (57.7)	71.3	0.13	**0.04**	**<0.01**
(kW m-1)	severe	26355 (8298)	3154 (1598)	6135 (1084)	123.7 (123.7)	71.5	0.13	**0.04**	**<0.01**
Probability of	moderate	21.0 (7.0)	10 (10)	14.3 (5.6)	0.3 (0.3)	38.5	0.84	0.82	0.27
Ignition (%)	severe	21.0 (7.0)	10 (10)	14.3 (5.6)	0.3 (0.3)	38.5	0.84	0.82	0.27

Table 3. Rates of land cover change at Makua Military Reservation and Schofield Barracks from 1950 to 2011. Change is given in units of average hectares per year for each date range. Total size for study areas are as follows: Schofield Grass, 745 ha; Schofield Forest, 1576 ha, Makua Grass, 320 ha; and Makua Forest, 1244 ha.

		1950-1962	1962-1977	1977-1992	1992-2004	2004-2011	1950-2011 (mean)
Schofield Grass	grass	3.0	1.2	2.6	0.7	-5.5	1.2
	woody	-2.0	-0.7	-3.2	-1.5	-4.6	-2.1
	bare ground	0.0	-0.1	0.0	0.2	-0.5	0.0
	developed	0.0	0.0	0.0	0.0	0.0	0.0
	shadow	0.0	0.0	0.0	0.0	0.0	0.0
	MTA	-1.0	-0.4	0.5	0.6	10.6	0.9
Schofield Forest	grass	-8.4	-7.3	-2.7	-1.0	-1.1	-4.5
	woody	-0.7	10.8	5.3	0.6	0.7	4.0
	bare ground	0.9	-0.9	0.0	0.4	-0.7	0.0
	developed	0.0	0.0	-0.4	-0.2	0.9	-0.1
	shadow	8.5	-4.3	-2.7	0.0	0.0	-0.1
	MTA	-0.3	1.8	0.5	0.2	0.1	0.5
			1962-1977	**1977-1993**	**1993-2004**	**2004-2010**	**1962-2010 (mean)**
Makua Grass	grass		7.4	5.0	-6.3	6.8	3.4
	shrub		-5.7	-6.6	8.1	-6.7	-3.0
	tree		-1.9	0.2	-0.2	0.0	-0.6
	bare ground		0.2	0.7	-1.1	-0.1	0.0
	developed		0.0	0.0	0.0	0.0	0.0
	shadow		0.0	0.0	0.0	0.0	0.0
	MTA		0.0	0.8	-0.5	0.0	0.2
Makua Forest	grass		0.8	9.5	-2.3	10.6	4.2
	shrub		2.0	-1.0	3.9	-19.9	-1.3
	tree		1.0	-1.4	3.3	8.7	1.7
	bare ground		0.4	-0.2	0.1	0.0	0.1
	developed		0.0	0.0	0.0	0.0	0.0
	shadow		-4.2	-6.8	-4.9	0.5	-4.6
	MTA		0.0	0.0	0.0	0.0	0.0

Figure 1. Location of sites for grassland and forest fuels sampling and historical analysis on the Waianae Coast and North Shores of Oahu, Hawaii. Forest and grassland field sampling occurred at Dillingham Airfield and Waianae Kai Forest Reserve. Historical land cover change analyses were conducted on imagery from Schofield Barracks and Makua Military Reservation.

Figure 2. Land cover at Makua Military Reservation on leeward Oahu, Hawaii from 1962 through 2010. The area inside the firebreak is heavily utilized for military training activities, and fire is frequent. The area outside the firebreak has historically been forested, has many threatened and endangered species, and is impacted to a lesser extent by military activities and fire.

Figure 3. Land cover at Schofield Barracks on leeward Oahu, Hawaii from 1950 through 2011. The area inside the firebreak is heavily utilized for military training activities, and fire is frequent. The area outside the firebreak is maintained for woody species, and is less affected by military activity and fire.

Figure 4. Change in grass, tree, and shrub land cover classes from 1962-2011 at Makua Military Reservation. Areas of interest (AIO) include: a) heavily utilized grassland area inside firebreak, b) nonnative forest area outside firebreak, and c) the entire Makua complex (both AOI's combined).

Figure 5. Change in grass, woody, and military training area land cover classes from 1950-2011 at Schofield Barracks. Areas of interest (AIO) include: a) heavily utilized grassland area inside firebreak, b) nonnative forest area outside firebreak, and c) the entire Schofield Barracks complex (both AOI's combined).

Figure 6. Landscape metrics: a) number of patches, b) contagion, and c) perimeter:area ratio for Forest and Grass areas of interest (AOI) at Schofield Barracks and Makua Military Reservation from 1950-2011.

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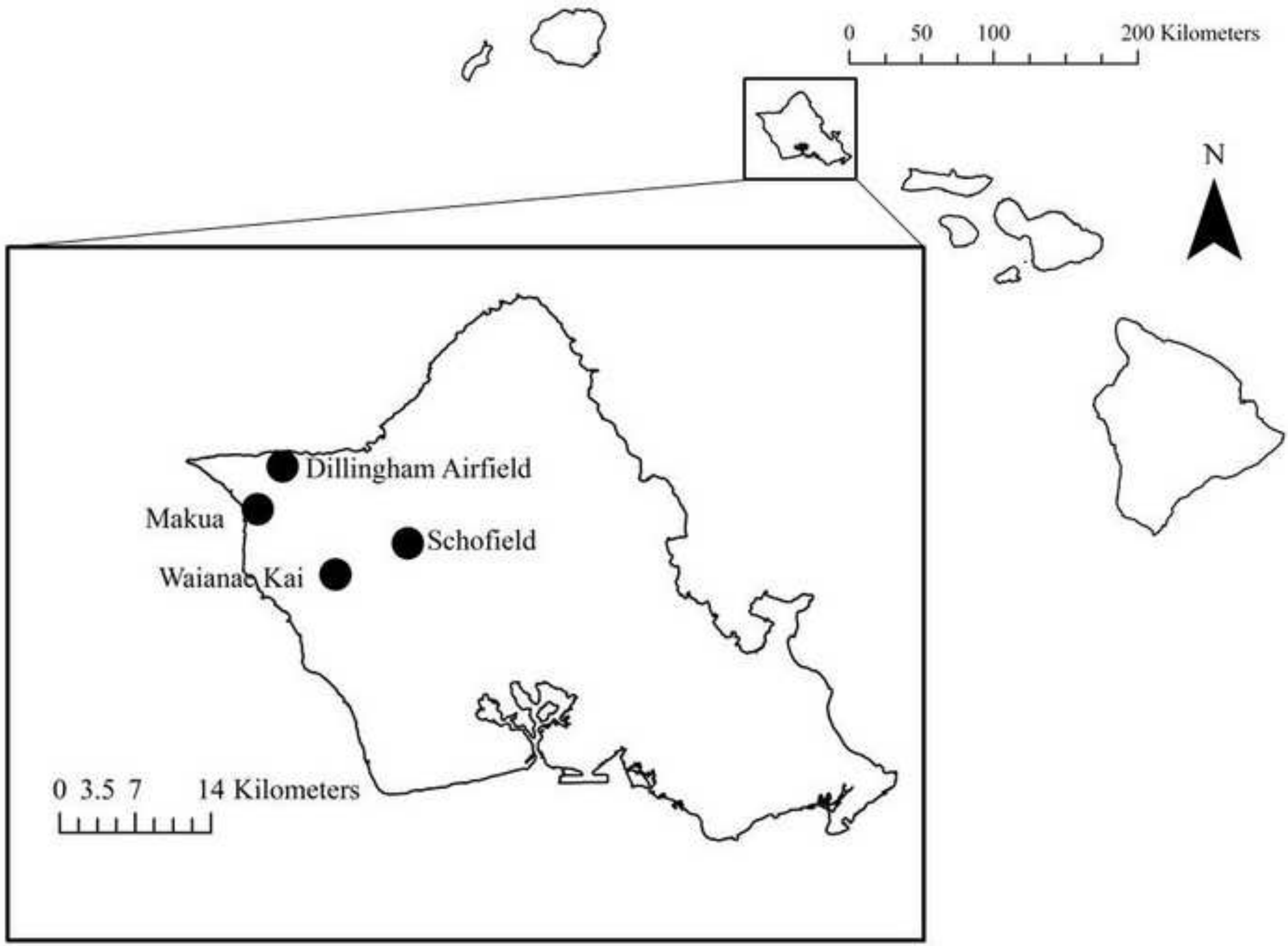

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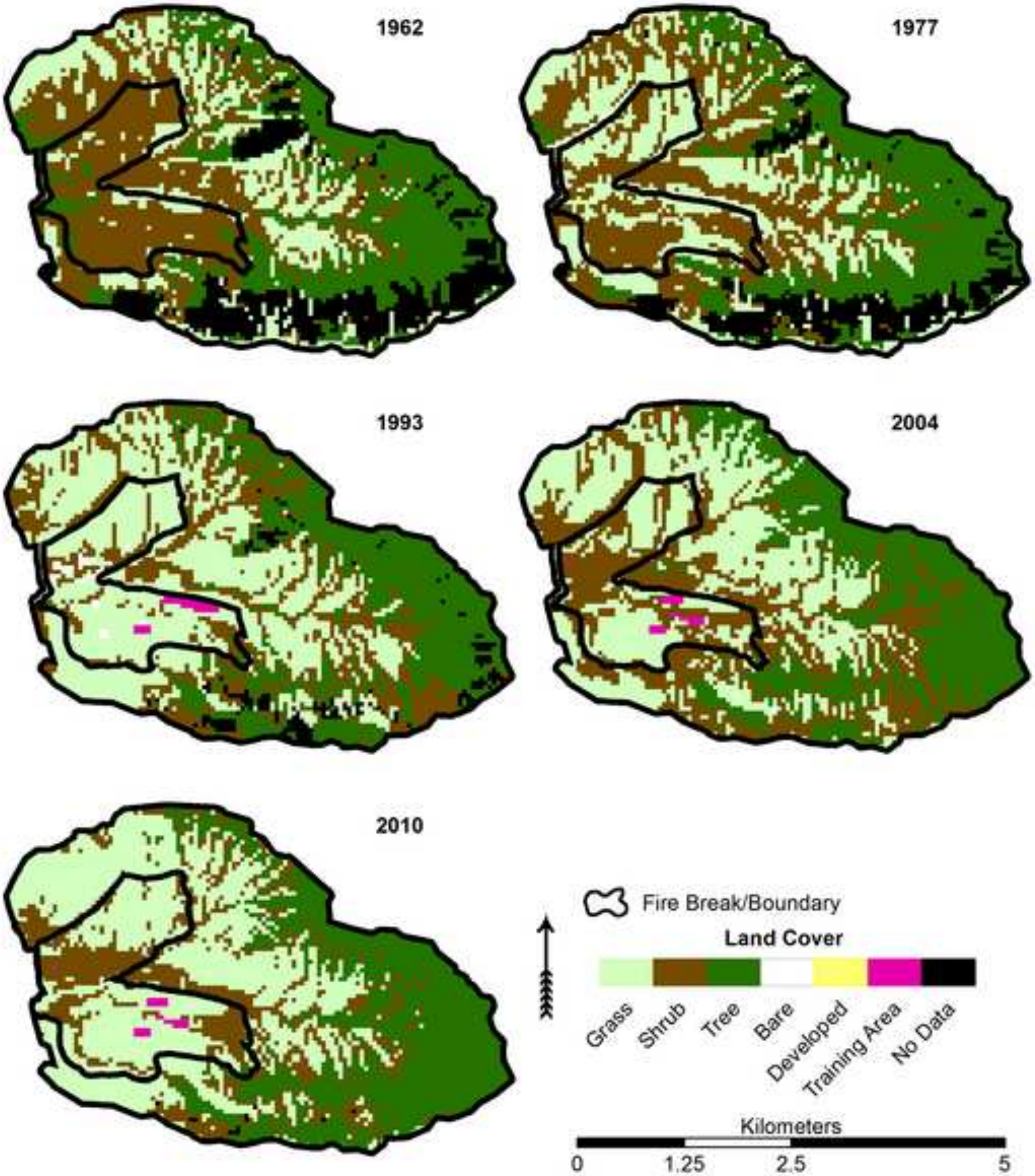

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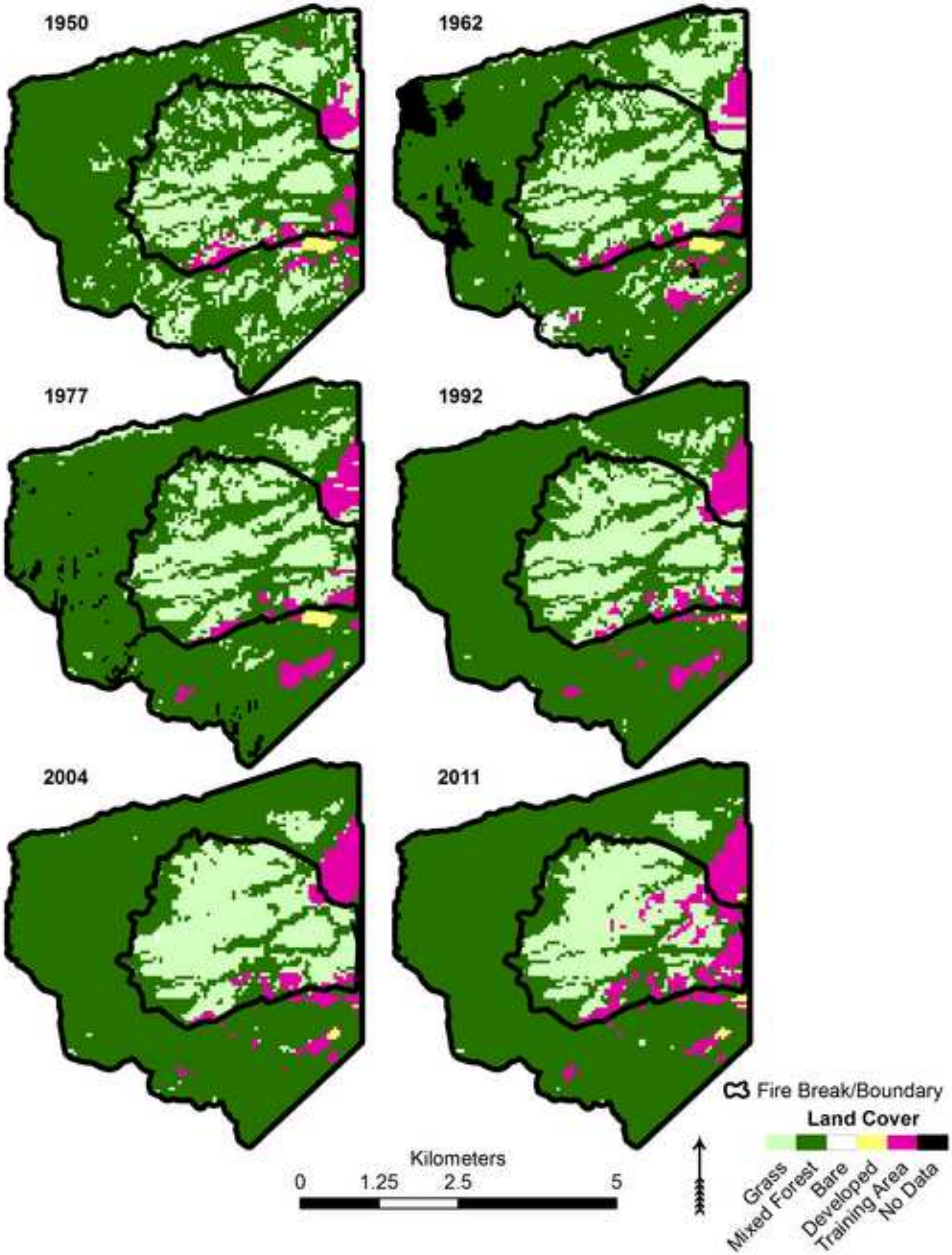

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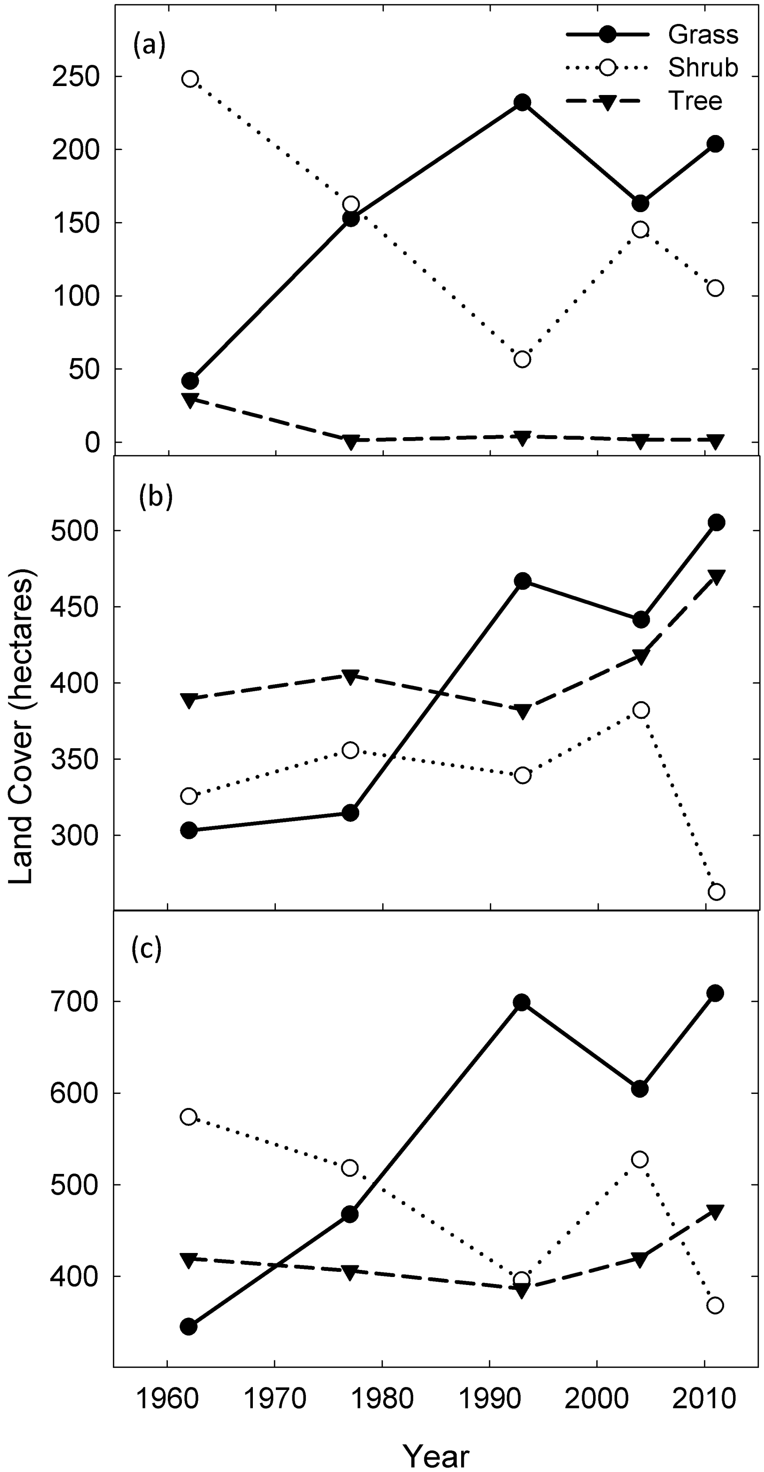

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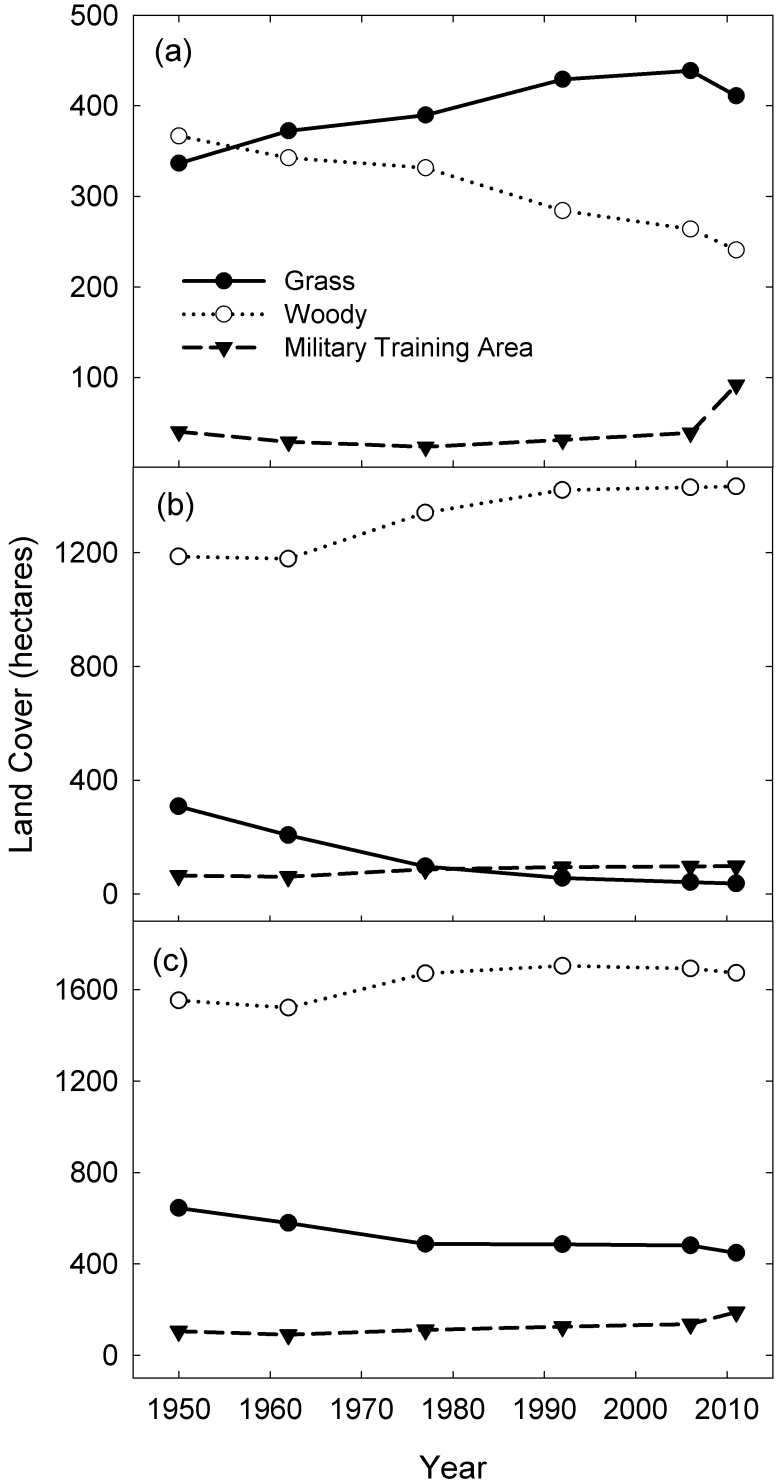

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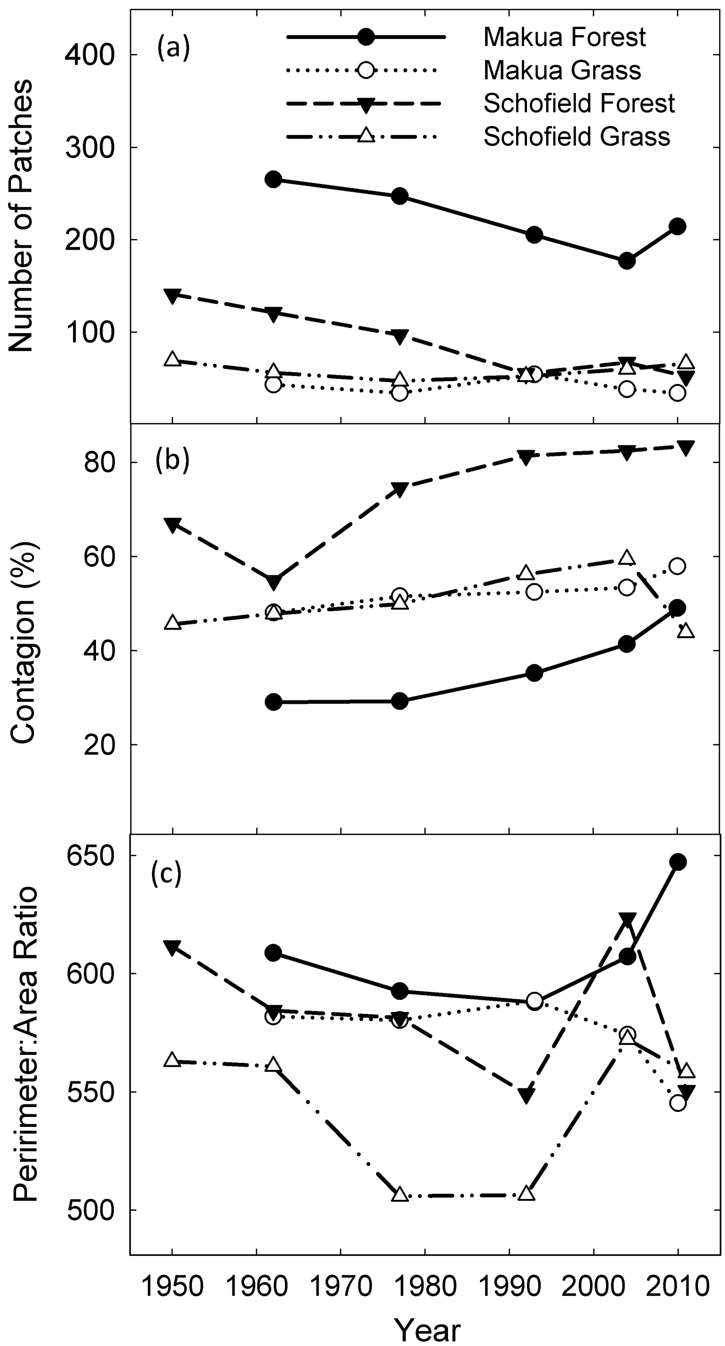

We test whether fire causes large-scale conversions of tropical forest to grassland

Fine fuel loads and moisture did not vary between grassland and adjacent forest

Surface fuel height was 31% lower in forest than adjacent grassland

Predicted fire behavior was more intense in grasslands than forests

Data support the paradigm that fire converts forest to grassland on tropical islands