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Hydrological effects of tree invasion on a dry coastal Hawaiian ecosystem

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ABSTRACT

In ecosystems invaded by non-native plants invasion effects are often spatially variable, and this variability is difficult to capture via plot-scale sampling. We used airborne high-resolution LiDAR (Light Detection and Ranging) to generate spatially explicit and contiguous information on hydrological effects of invasive trees (*Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth). We developed regression relationships between LiDAR metrics (i.e., ground elevation and tree canopy height) and plot-scale measurements of vegetation stem water $\delta^{18}O$, to assess groundwater use, and transpiration rates. We used electrical resistivity imaging to assess sub-surface geology and hydrology and their relationships to *P. pallida* stand structure. *P. pallida* biomass and transpiration varied greatly across the study area; both were controlled by depth to groundwater. Stem water $\delta^{18}O$ values (-8.6 to 3.7‰) indicated a threshold ground elevation of ca. 15 m above sea level, above which *P. pallida* could not access groundwater; this threshold corresponded to declines in tree biomass and height. Transpiration modelled across the study area was 0.034 ± 0.017 mm day^{-1}, but over 98% of transpiration came from the ca. 25% of the total study area where groundwater depths were less than 15 m. Our combination of methods offers a new way to incorporate fine-scale spatial variation into estimation of plant invasion effects on hydrology, increase our understanding of interactions of geology, hydrology, and biology in such invasions, and prioritise areas for control in well-advanced invasions.

1. Introduction

In arid and semi-arid (dryland) environments, geological and climatic controls of water availability typically determine distributions of organisms and ecosystem dynamics (Noy-Meir 1973, Austin et al. 2004). In turn, biota often exert powerful feedbacks on the hydrologic processes of these dry environments (Huxman et al. 2005). Because these processes are inextricably linked, multidisciplinary approaches are needed to examine controls of biological invasions in drylands (Newman et al. 2006, Jackson et al. 2009). The need to understand relationships between invasive plants and their hydrologic setting will become still more pressing as climate change alters these dryland systems through time. Such knowledge may aid preparation for, and reduction of, ecological and socioeconomic impacts that follow ecosystem change (Clark et al. 2001).

Transpiration by phreatophytic vegetation (deep-rooted plants that obtain much of their water from the phreatic zone and its capillary fringe) can remove considerable quantities of water from aquifers (Thorburn et al. 1993, Naumburg et al. 2005). Changes in phreatophyte abundance - such as introductions of invasive phreatophyte species or removal of large trees in place of shallow-rooted crops - may profoundly affect regional hydrology and soil chemistry. Increased groundwater transpiration by phreatophytes may reduce base flow (Le Maitre et al. 2000, Dahm et al. 2002) to the detriment of aquatic communities (Dewson et al. 2007). In contrast, reduced groundwater table depth following deforestation of native phreatophytes has contributed to widespread and costly salination of croplands across many of Australia's dryland regions (White et al. 2002, Hatton et al. 2003, Rengasamy 2006). Methodological challenges exist in quantifying the effects of phreatophytes when vegetation density varies across large

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spatial scales (Le Maitre et al. 2000). Process-based understanding of such spatial variation is increasingly acknowledged as critical to comprehensive understanding of biogeochemical impacts in invaded ecosystems (Hultine et al. 2006, Rascher et al. 2012, Hughes et al. 2014).

On leeward coasts of the Hawaiian Islands, groundwater plays an important role in the structure and function of terrestrial, estuarine, and marine ecosystems. The bulk of leeward rainfall falls in high elevation cloud forests, while coastal environments receive substantially less rainfall (~270 mm; Giambelluca et al. 2013). The highly fractured and porous nature of basalt lava flows of the region coupled with low amounts of rainfall on leeward sides of the Hawaiian Islands results in upslope groundwater flow being the major hydrologic connection of land to sea and the major freshwater input to coastal marine systems on leeward sides of islands (Lau and Mink 2006, Johnson et al. 2008, Peterson et al. 2009). This groundwater flow to the coast as submarine groundwater discharge (SGD) provides cool, nutrient rich freshwater that sustains the productivity of communities in nearshore environments, including keystone marine species such as Hawai‘i ’s indigenous marine algae (Peterson et al. 2009, Duarte et al. 2010). Because it is derived from high-altitude recharge, groundwater in this area is isotopically distinct from most low-altitude rainfall events, allowing it to be traced through lowland ecosystems (Scholl et al. 1996, Dudley et al. 2014).

The impacts of *Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth, a phreatophytic invader to Hawai‘i, have been shown to be heavily influenced by spatial patterns of groundwater availability. Dudley et al. (2014) documented groundwater-dependent differences in tree physiology, stand structure and soil chemistry in coastal forests of *P. pallida*. Trees in areas where stem water δ^{18}O values indicated uptake of groundwater (less than ca. 15 m above sea level) showed physiological evidence of greater water availability, including higher stem water potential, higher pre-dawn photosynthetic yield, and lower water use efficiency than trees nearby for which stem water δ^{18}O values indicated a reliance on local rainfall. Productivity, nitrogen (N) fixation rates, soil N, carbon (C) and phosphorus (P) content were all substantially greater in areas where *P. pallida* had access to groundwater compared to where it did not. While *P. pallida* is adapted to survive in very dry conditions without available groundwater, in areas where groundwater was present within the rooting zone it forms tall, dense and often monospecific stands (Miyazawa et al. 2016). Since the introduction of *P. pallida* to Hawai‘i in 1828*, Prosopis*-dominated dry forest and shrubland has spread to cover approximately 3.5% of the total land area of the Hawaiian archipelago (ca. 59,000 ha), predominantly along lowland, arid leeward coasts (Gallaher and Merlin 2010). Young lava substrates along these coasts tend to be devoid of deep-rooted vegetation, and *P. pallida* stand establishment widely represents afforestation rather than competitive displacement of other tree species. Rates of transpiration of groundwater by dense stands of *Prosopis* spp. in the southeastern United States have been previously estimated to range from 374 to 750 mm yr^{-1} (Scott et al. 2000, Scott et al. 2004, Scott et al. 2008), although transpiration on the lava of leeward Hawai‘i may be lower, particularly during periods of drought (Miyazawa et al. 2016). Such flow rates may diminish both groundwater availability for human use and flows of groundwater to near-shore marine environments. An understanding of spatial patterns of transpiration rates in these phreatophytic plant communities will inform assessments of their impacts to groundwater resources as well as spatial patterns of their impacts to soils and ecosystem function.

In this study, our aims were to accurately incorporate the heterogeneity of these forests in assessment of transpiration during a drought period and identify areas where impacts of the invasion were likely to be greatest. This latter aim would inform on the potential to focus biological control of this species in areas of greatest impact.

For this, we collected biomass, stem water δ^{18}O, and transpiration data from ground measurements during a drought period and scaled-up these measurements to the entire area of interest by developing relationships between them and airborne LiDAR metrics (canopy height and elevation). We used electrical resistivity imaging of subsurface geology to identify depth to water table and substrate heterogeneity along multiple coastal-to-upland transects within this coastal riparian stand of *P. pallida*. We also related depth-to-water to tree height along transects and along the entirety of Kīholo Bay coastal area using wall-to-wall inventories of tree height obtained from LiDAR data.

We hypothesized firstly that a ground elevation could be identified above which *P. pallida* in this area can no longer access groundwater, due to physiological limitations of the tree's hydraulic system. Secondly, we hypothesized that *P. pallida* biomass and transpiration rates – and thus influence on groundwater discharge – below this elevation would be significantly higher than the average across the stand.

2. Methods

2.1. Study system

The study was conducted along the coastline within the boundaries of Kīholo State Park on the western, leeward coast of Hawai‘i Island (lat. 19.84°, lon. −155.93°). Mean annual precipitation of the area over the 30 years prior to the study was ca. 270 mm (Giambelluca et al. 2013) and mean annual temperature of the area between September 30, 2010 and September 30, 2012 was ca. 24 °C. Rainfall typically occurs as sporadic small events in summer months and larger events between October and March (Giambelluca et al. 1986).

During dry periods, the area consists of monospecific *P. pallida* stands which have established and proliferated from individuals planted in leeward Hawai‘i in the latter 19th century and early 20th century (Maly and Maly 2011). The invasive spread of this species away from planted stands occurred rapidly, largely due to dispersal of seeds by goats or cattle (Gallaher and Merlin 2010). These stands are augmented by an ephemeral understory cover of native herbs, *Sida fallax* Walp. (‘Ilima) and *Waltheria indica* L. (‘Uhaloa) following large rain events. The geology is comprised of contiguous pāhoehoe and ‘a‘ā basalt bedrock that is derived from lava flows ca. 3,000 – 10,000 ybp (Wolfe and Morris 1996). Soil in the area typically occurs as a thin (i.e., depth ca. 4 cm) discontinuous layer over this flow (Dudley et al. 2014). Lava flows originated from Hualālai Volcano, and their morphology includes groundwater-bearing subsurface channels (Bauer 2003). Aerial thermal infrared imaging of the coastline (Adams et al. 1971, Johnson et al. 2008), aerial magnotelluric and electrical resistivity reconnaissance (Adams et al., 1971), and surveys for geochemical tracers of groundwater (Street et al. 2008, Peterson et al. 2009, Knee et al. 2010) indicate that groundwater flow is limited to a basal aquifer connected to the ocean, with water exiting from the coastal region of the site via subsurface lava tubes and voids between layers of lava flows.

Within this area we established ten transects for measurement of δ^{18}O of stem water (T1-T10), two further sets of five 20 m-radius reference plots (L1-L5, U1-U5) to measure δ^{18}O of stem water, four transects to measure depth to ground water (A-D), and LiDAR over the whole site to measure elevation, and tree canopy height. Rainfall δ^{18}O and sapflow were measured at reference plots L1 and U1. Tree density and stem diameters were measured in all plots within three of the ten stem water transects, and all reference plots (Fig. 1).

2.2. Determination of belowground structure and depth to groundwater

We used electric resistivity tomography to identify heterogeneity in subsurface geologic structures and to locate groundwater along established transects. Ground resistivity is related to mineral content, porosity, and water saturation of the rock. Hence, this technique allows for a differentiation of low-resistivity groundwater-saturated layers from higher-resistivity unsaturated lava flows, fractures and voids. We recorded bulk apparent resistivity (Ohm-m) of the geologic substrate using an electrode array. The apparent resistivity cross sections were