Effects of native forest restoration on soil hydraulic properties, Auwahi, Maui, Hawaiian Islands

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[1] Over historic time Hawai'i's dryland forests have been largely replaced by grasslands for grazing livestock. On-going efforts have been undertaken to restore dryland forests to bring back native species and reduce erosion. The reestablishment of native ecosystems on land severely degraded by long-term alternative use requires reversal of the impacts of erosion, organic-matter loss, and soil structural damage on soil hydraulic properties. This issue is perhaps especially critical in dryland forests where the soil must facilitate native plants' optimal use of limited water. These reforestation efforts depend on restoring soil ecological function, including soil hydraulic properties. We hypothesized that reforestation can measurably change soil hydraulic properties over restoration timescales. At a site on the island of Maui (Hawai'i, USA), we measured infiltration capacity, hydrophobicity, and abundance of preferential flow channels in a deforested grassland and in an adjacent area where active reforestation has been going on for fourteen years. Compared to the nearby deforested rangeland, mean field-saturated hydraulic conductivity in the newly restored forest measured by 55 infiltrometer tests was greater by a factor of 2.0. Hydrophobicity on an 8-point scale increased from average category 6.0 to 6.9. A 4-point empirical categorization of preferentiality in subsurface wetting patterns increased from an average 1.3 in grasslands to 2.6 in the restored forest. All of these changes act to distribute infiltrated water faster and deeper, as appropriate for native plant needs. This study indicates that vegetation restoration can lead to ecohydrologically important changes in soil hydraulic properties over decadal time scales. **Citation:** Perkins, K. S., J. R. Nimmo, and A. C. Medeiros (2012), Effects of native forest restoration on soil hydraulic properties, Auwahi, Maui, Hawaiian Islands, *Geophys. Res. Lett.*, *39*, L05405, doi:10.1029/2012GL051120.

1. Introduction

[2] Dryland forests in Hawai'i have been heavily impacted by land use changes; less than 10% of original dryland forest habitat remains [*Cabin et al.*, 2000; *Rock*, 1913; *Medeiros et al.*, 1986]. Much of the loss resulted from 19th century expansion of cattle and other ungulate grazing leading to the replacement for dryland forest with grasslands [*Cabin et al.*, 2000]. Invasive grasses prevented native plant regeneration [*D'Antonio and Vitousek*, 1992] and changed soil hydraulic properties to favor invasive species. We hypothesize that reestablishment of native species may reverse these soil hydraulic property changes over relatively short time scales (e.g., decades). Improved characterization of how this process occurs is crucial for understanding long-term impacts of restoration on ecology in this rapidly changing environment.

[3] In 1997, land owners, resource managers, scientists, and volunteers began an effort to restore the dryland forest of Auwahi, on the leeward slope of Haleakalā, Maui (Figure 1). They aimed to restore an endangered native ecosystem [*Bruegmann*, 1996; *Pau et al.*, 2009] that was once an important resource for ancient Hawaiians [*Medeiros*, 2003; *Medeiros et al.*, 1998]. A 10 acre tract was chosen at about 1220 m elevation and fenced to exclude grazing animals, grass, and other invasive species. Mats of the invasive kikuyu grass (*Pennisetum clandestinum*) were eliminated with herbicides, and the tract was

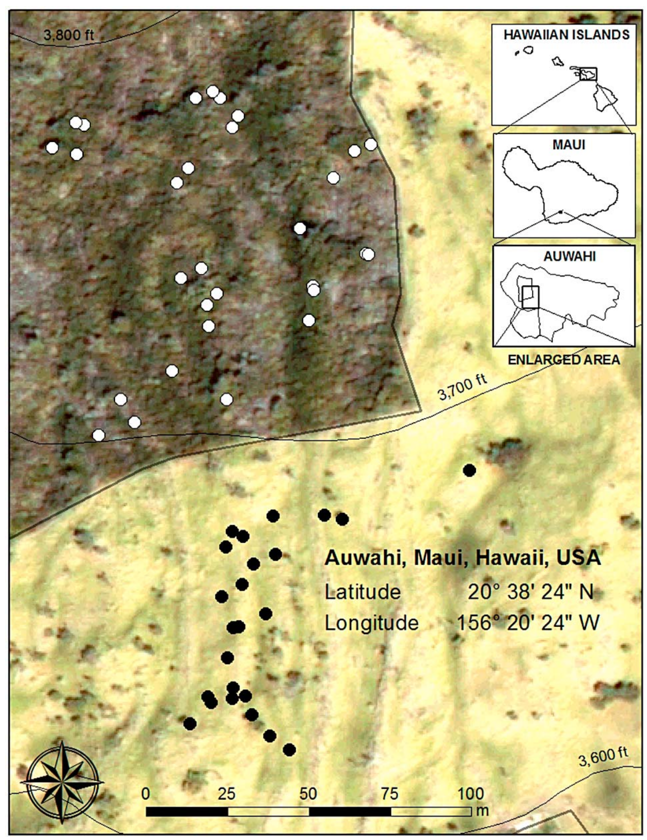

Figure 1. Location of the Auwahi study area. Measurement locations within the exclosure (dark, vegetated area) are indicated by open circles and measurements within the deforested rangeland are indicated by solid circles.

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Table 1. The 8 Point Hydrophobiciy Scale of *Doerr* [1998]

Class	Descriptive Label	Ethanol %
7	Extremely hydrophobic	36
6	Very strongly hydrophobic	24
5	Strongly hydrophobic	13
4	Moderately hydrophobic	8.5
3	Slightly hydrophobic	5
2	Hydrophillic	3
1	Very hydrophillic	0

replanted with quick-growing native tree, shrub, vine, and grass species that were elements of the original community. Less than 15 years later the forest is thriving [*Medeiros et al.*, 2003, 2007], an additional 40 acres have been successfully reforested and Auwahi is now considered one of the most successful restoration projects and the most diverse dryland forest in Hawai'i [*Medeiros et al.*, 2007; *Cabin*, 2011].

[4] Several studies in Hawaii have demonstrated the likely effects of the loss of native forest on the near-surface hydrology [*Stock et al.*, 2003; *Scholl et al.*, 2007], as well as the effect of native vegetation on water inputs to soil [*Giambelluca et al.*, 2011], but the role of soil hydraulic properties and subsurface moisture dynamics as influenced by vegetation, have not been investigated using direct field measurements. Vegetation can modify soil properties in measureable ways over decadal time scales, influencing the availability of water to root systems and reducing evaporative and drainage losses [*D'Odorico et al.*, 2007; *Grayson et al.*, 2006; *Nimmo et al.*, 2009a; *Sandvig and Phillips*, 2006]. Changes in land use can significantly alter the hydraulic properties that effect these processes [*Berglund et al.*, 1980; *Godsey and Elsenbeer*, 2002; *Wahren et al.*, 2009; *Zimmermann et al.*, 2006]. Hawaiian dryland forests receive about 730 mm of rain per year with additional moisture inputs from cloud water interception [*Giambelluca et al.*, 2011]. Studies on the reestablishment of native species at the Auwahi reforestation area in Maui have focused primarily on above-ground processes, from the leaf-litter layer up through the canopy [*Giambelluca et al.*, 2011; *Medeiros*, 2006; *Medeiros et al.*, 2007]. However, understanding the role of the underlying soils in regulating water flow through this complex ecosystem is also critical in assessing the influence of changes in vegetation and climate on plant-available water and aquifer recharge. The main objective of this study is to examine how successful reestablishment of native species influences shallow soil hydraulic properties in a species-diverse dryland forest setting on a decadal scale. Further studies will be needed to examine hydraulic properties and changes in soil moisture over time at greater depths which will provide insight into deeper drainage.

2. Methods

[5] We measured field-saturated hydraulic conductivity (K_{fs}) with the method of *Nimmo et al.* [2009b], which employs a portable, falling-head, small-diameter (∼20 cm) single-ring infiltrometer and an analytical formula for K_{fs}, to compensate for both variable falling head and subsurface radial spreading that unavoidably occurs with small ring size. The method, though perhaps in some respects not as robust as others described in the literature, allows for a large number of measurements relatively rapidly and is suitable for comparative studies at field sites such as Auwahi that have very limited accessibility and extremely rugged terrain. We applied this method at 24 locations in the invasive grassland and at 31 locations in the reforested exclosure (Figure 1). Within the exclosure, the infiltrometers were placed beneath the canopy about 30-50 cm from the plant stem with any loose litter removed from the soil surface to ensure that no leakage occurred. In the grassland, grass was also cleared from the soil surface to avoid leakage. Hydrophobicity measurements were taken using molarity of ethanol droplet (MED) tests as implemented by *Doerr* [1998], using an 8-point scale. The test is designed to use the rapidity of infiltration of droplets of water with varying ethanol concentrations as a metric for hydrophobicity. Solutions were mixed with ethanol concentrations of 0, 3, 5, 8.5, 13, 24, and 36 percent by volume diluted with deionized water. Time for droplet penetration was measured and soils were rated according to Table 1. The rating corresponds to the highest concentration of droplet that penetrated the soil in under 3 seconds. The eighth point of the scale is implicit as the possibility that for soils at the highest extremes of hydrophobicity the 36-percent solution may not penetrate in less than 3 seconds. As there are no established methods for measuring preferential flow, we used a coarse rating scale of 0 to 3 by examination of the pattern of dry vs. wetted soil area on excavating from the surface downward after the infiltration has ceased. A rating of 0 indicates no preferential flow (uniform, symmetric wetted pattern), 1 is slightly preferential (irregularly-shaped wetted pattern), 2 is moderately preferential (with one or more isolated wetted areas distinct from main wetted area), and 3 is highly preferential (multiple isolated wetted areas with no obvious main one). Soils with three different dominant species were examined: invasive kikuyu grass (*Pennisetum clandestinum*), native *olopua* (*Nestegis sandwicensis*), and native ‘*a*‘*ali*‘*i* (*Dodonaea viscosa*). Data were compared in terms of native and

Table 2. Mean and Standard Deviation Values for Kfs, Hydrophobicity, and Flow Preferentiality[a]

Species	Number of Samples in Each Test	K_{fs} Mean Value (cm/s)	K_{fs} Standard Deviation	Hydrophobicity Mean Value	Hydrophobicity Standard Deviation	Preferentiality Mean Value	Preferentiality Standard Deviation
Invasive kikuyu grass	24	0.038	0.0259	6.00	0.66	1.32	0.65
Native *olopua*	14	0.072	0.0358	6.90	0.32	2.35	0.70
Native ‘*a*‘*ali*‘*i*	17	0.055	0.0252	6.95	0.51	2.90	0.32
Olopua and ‘*a*‘*ali*‘*i*	31	0.067	0.0334	6.93	0.45	2.56	0.64

[a]Values are given for individual species dominant at the measurement location as well as the native species combined.

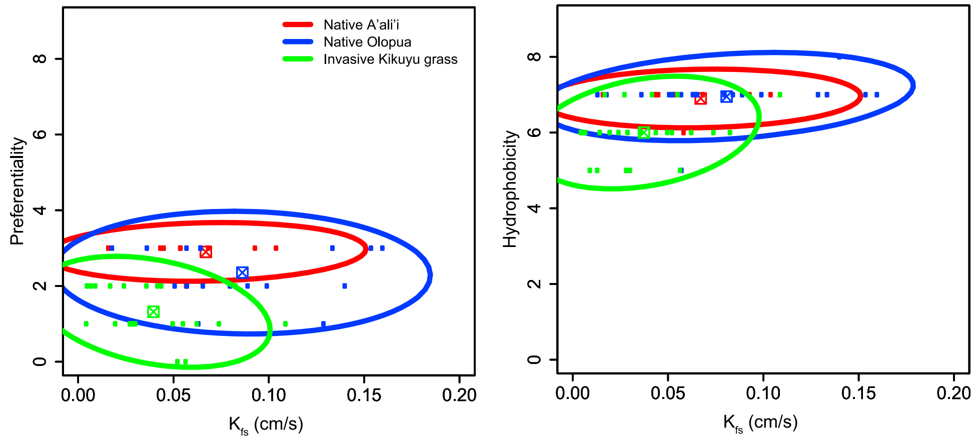

Figure 2. Plots of hydrophobicity and preferentiality vs. field-saturated hydraulic conductivity. Small dots are measured values, squares are mean values and ellipses indicate the 95% confidence intervals.

invasive categories and further examined by dominant native species at the location of the measurement to look at within-exclosure effects. Statistical significance was determined using two sample t-tests assuming unequal variance at the 95 and 99 percent level.

3. Results and Discussion

[6] Results from 55 tests support the hypothesis that reforestation at the Auwahi site has significantly altered plant-relevant soil hydraulic properties. Table 2 shows that mean values of K_{fs}, hydrophobicity, and preferentiality are systematically higher for the native species (individually and combined) than for the grassland. Mean K_{fs} in the restored forest measured by infiltrometer tests was greater by a factor of 2.0. Hydrophobicity on an 8-point scale increased from average category 6.0 to average category 6.9. A 4-point empirical categorization of preferentiality in subsurface wetting patterns increased from an average 1.3 to 2.6. Figure 2, plots of hydrophobicity and preferentiality vs. K_{fs}, clearly illustrate the shift in properties with revegetation that favors the deeper-rooting natives. Between measurements inside and outside the exclosure, differences in K_{fs}, hydrophobicity, and preferentiality of flow are significant at the 99% confidence level. K_{fs} values are also significantly different between the two dominate native species within the exclosure (*olopua* and ‘*a*‘*ali*‘*i*) at the 95% confidence level. Differences in preferentiality of flow between the *olopua* and ‘*a*‘*ali*‘*i* are also significant at the 95% confidence level with no significant difference in hydrophobicity.

[7] These results illustrate the important influence of vegetation on subsurface hydrologic processes. Results indicate that plants have the ability to alter soil properties on decadal time scales to facilitate optimal growth by promoting efficient water use.

4. Summary

[8] Soils on degraded landscapes present a challenge to restoration of native ecosystems. Severe erosion, organic-matter loss, and structural damage from periods of alternative land use such as grazing destroy nutritional and water-distributing soil characteristics that are crucial to reintroduced native species. Measurements within a reforested area and adjacent grassland show that reforestation increases field-saturated hydraulic conductivity, preferential flow, and hydrophobicity. All of the soil hydraulic property changes observed in this study act to distribute infiltrated water faster and deeper, as appropriate for native plant needs. These results indicate that native dryland forest restoration can effect ecohydrologically important changes in soil-water characteristics which in turn promote the overall health of resident native forests.

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