THE INFLUENCE OF NON-NATIVE, MONOTYPIC FOREST PLANTATIONS ON SOIL HYDROLOGIC PROPERTIES WITHIN THE HONOULIULI PRESERVE, O'AHU, HAWAI'I

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARTS

IN

GEOGRAPHY

AUGUST 2003

By
Jeffrey N. Nagel

Thesis Committee:

Thomas W. Giambelluca, Chairperson
Ross Sutherland
Everett Wingert

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Arts in Geography.

THESIS COMMITTEE

Chairperson

Dedication

I would like to dedicate this final product to my loving parents, for without their constant love and support this would not have come to print. I Love you both – Mahalo!

Acknowledgements

I would like to acknowledge first and foremost my advisor Tom Giambelluca for guiding me through this project and taking me under his wing in time of need. Ross Sutherland for his statistical insight, geomorphology lab equipment, storing over 1,000 bags of soil, and for his timely and thorough editing. Ev Wingert for his expertise in refining my field mapping techniques. T. Vana for his continuous assistance even when he was overwhelmed with his own work. A. Ziegler for his advice, ideas, and project setup. G. Shen for throwing me in the loop for a 2 year tuition waiver. The Nature Conservancy for offering me this opportunity to work with them in such a unique place in O'ahu and for their support of vehicles, passes, mapping, and basically hanging in there for the long haul – a great crew to work with – Dan, Joan, Pauline, Trae, Lance, and Nat. G. Laliberte for assisting in the final map production. K. Nolan, J. Myhre, J. Silver, and D. Olsen for initial map generation. T. Restom for familiarizing me with Honouliuli, offering advice, and pushing me for data. J. Garrison for providing some of her findings. D. Woodcock for the initial interest in forest plantations. C. Nolan for his help in hauling 20 gallons of water to 'the top' at high noon. T. Frost and J. Huber for field assistance in the early stages. E. West, S. Kang, J. Myhre, P. Fidopiastis, A. Ta, K. Nolan, T. Vas Dias, G., L., and E. Laliberte, M. Kollaros, L. Clint, S. Cavanaugh, and R. Nagel for joining me the pursuit of 'the better things in life' - moving with the fluid motion of water to ease the soul between field, lab, and writing time. Kewalo Marine Lab, UH Leisure Program, and the U.S. Coast Guard District 14 ole staff for understanding the rigors of school and offering flexible work hours and the finances to 'get by'. Finally, to Hawai'i – a place I can call home.

Abstract

Efforts to revegetate the denuded landscapes of the Hawaiian Islands began in the late 1800s. In an attempt to protect the watersheds, improve the water cycle, and prevent further surface runoff and soil erosion, millions of non-native trees were planted in monotypic forest stands. The Honouliuli Preserve, in the Wai'anae Mountains on the island of O'ahu, contains examples of this reforestation effort. Hydrologic properties were examined under monotypic stands of *Eucalyptus*, *Fraxinus*, and *Acacia* species for two separate soil types (alfisols and inceptisols) in the Honouliuli Preserve, as well as control plots outside of the preserve that contained a grass species *T. insularis*. The study was conducted to evaluate how monotypic forest plantations affect near-surface hydrologic processes. Saturated hydraulic conductivity (K_s), bulk density, and organic matter content were measured in roughly 200 sampling sites. A water-repellent soil characteristic, found in three of the forest plots and one control plot, and existing in both soil types, dramatically influenced K_s and reduced correlations between K_s and bulk density and between K_s and organic matter content. As is typical of K_s measurements, infiltration rates were highly variable spatially, both in the water-repellent soils and the 'wettable' soils. These findings suggest that the water-repellency of the forest soils were likely caused by chemicals in the vegetative litter and leaves and correlated with the allelopathic species (*E. robusta* and *A. confusa*). The water-repellent nature of the control plot in the inceptisol may have been the result of past fires used to clear the grass. The forests benefit the landscape by decreasing soil bulk density and thus increase infiltration rates, yet the forest species that create water-repellent soil surfaces decrease infiltration rates creating a negative effect on the region. The net effect is that forest plantations are

an improvement to the hydrologic properties of the soil in comparison to the denuded landscape prior to planting.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Early in the 19th century, agriculture, fires, and intensive overgrazing of ungulates destroyed much of the native vegetation in Hawai'i (Cuddihy and Stone, 1990). With the landscape of O'ahu, Hawai'i denuded of native vegetative cover, and erosion and runoff high, trees were planted extensively on the island in the late 1800s and early 1900s. However, rather than re-planting the diverse native vegetation that originally composed the forests of Hawai'i, non-native forest species were chosen based on their potential to grow fast and propagate easily (Lyon, 1929; Whitesell and Walters, 1976).

There were many misconceptions at that time regarding the role of forest cover in the hydrologic cycle. Trees were planted with the goal of restoring consistent streamflows and steady recharge of aquifers (Hamilton and King, 1983), but the mechanisms by which the forests influence water processes were not well understood. Many foresters of the time promoted the idea that forests increased precipitation (Maxwell, 1898; Crosby, 1953). Others, however, believed that these monotypic forests would create adverse conditions on the landscape, such as consuming higher amounts of water (Cannell, 1999) and increasing the potential for erosion (Giffard, 1913; Judd, 1926).

Although early beliefs that forests 'produce' more water have proven to be incorrect, it is true that land cover can greatly affect hydrologic processes. Forests have high evapotranspiration rates, therefore losing water to the atmosphere at greater rates than grassland vegetation or regions lacking vegetation. However, forests also typically have high infiltration rates, benefiting water flows (Dunne and Leopold, 1978).

Land-use change can dramatically affect the hydrologic characteristics of soil, as well as the soil's physical and chemical properties. Wiersum (1985) determined that direct soil cover, consisting mainly of vegetative litter, is the single most important vegetative factor in protecting the soil surface from increased erosion and runoff, and considered canopy cover and understory less significant. However, in severely degraded landscapes, as is the case in Kaho'olawe, Hawai'i, revegetation efforts can substantially increase infiltration rates and thus reduce overland flow (Ziegler and Giambelluca, 1998). Prior to the establishment of the forest plantations on O'ahu, people spoke of severe erosion and witnessing overland flow (Schuyler and Allardt, 1889). Non-native, monotypic forests planted to protect the watersheds on O'ahu, often lacked understory growth but provided a substantial litter layer. Thus, a question arises; have these forest plantations resulted in improved infiltration rates (that is, are the rates higher) from that of the previously denuded landscape's infiltration rates?

1.1 Objectives

The goal of this study is to gain insight into the effects revegetation efforts (forest plantations) have had on the hydrologic characteristics of the soil on O'ahu. To investigate the effects of revegetation efforts on soil properties, infiltration rates, bulk density, and organic matter content are examined. This study sets out to provide a better understanding and evaluation of how monotypic forest plantations can affect near-surface hydrologic processes on O'ahu.

1.2 Background

In the mid 1800s, it was apparent that the native forests of the Hawaiian Islands were rapidly disappearing (Lyon, 1929). During this time, visitors to the islands spoke of large tracts of dying forests and barren landscapes (Crosby, 1953). Intensive agriculture and grazing livestock began to perturb the native vegetation on the islands, vegetation that had not evolved to cope with this type of attack (Lyon, 1929; Skolmen, 1962; Buck et al., 1988). The native forests of Hawai'i generally have a shallow root structure, and with the vast number of animals roaming freely in the forests grazing and trampling the forest floor, the forests perished (Maxwell, 1898; Crosby, 1953). Additional pressures were placed on the forests due to the sandalwood (*Santalum* sp.) trade, fires, and timber harvesting for fuelwood and fence posts (mainly for use by the sugar plantations), increasing the rate of deforestation (Judd, 1918; Whitesell and Walters, 1976). On O'ahu, the native vegetation was significantly diminished along the Ko'olau and Wai'anae mountain ranges, leaving exposed bare soil (Frierson, 1973). The exposed soil, combined with the steep terrain and periods of intense rainfall, provided ideal conditions for accelerated erosion (Giffard, 1913; Crosby, 1953).

With the loss of forests came the recognition that the forests provided a vital resource, and private landowners began fencing off remaining forests to cattle and other grazing animals (Maxwell, 1898). Reforestation efforts began on O'ahu around 1870 (Lubker, 1886; Walker, 1887), initially to control soil erosion (Nelson et al. 1968) and to supply additional fuelwood and fence posts for the sugar plantations (Bryan, 1957). Private landowners were instrumental and the first to make serious efforts at revegetation, planting a variety of native and introduced tree species (Hall, 1904). There was also an urgent need to maintain a steady supply of water to irrigate the fields, and thus, watershed protection became a real concern. Forests were believed to be the best land cover in this regard at this time (Lubker, 1886; Walker, 1887; Zschokke, 1930).

Native species were initially used in reforestation, but the vast majority of these plantings failed (Lyon, 1929; Whitesell and Walters, 1976). Native species were difficult to propagate in the nurseries, grew too slow to be effective (Judd, 1931), and in this newly altered landscape were difficult to reestablish successfully (Lyon, 1929). A wide variety of exotic tree species (such as several species of *Eucalyptus*, *Fraxinus*, and *Acacia*) were preferred for planting because they propagated easily and reestablished quickly on almost any degraded landscape with poor soil fertility (Lyon, 1929). However, these plantings, unlike the native Hawaiian forests, supported little vegetative undergrowth to protect the soil. The exotic forest plantations, intended to protect the watershed by decreasing soil erosion and increasing water infiltration into the soil, apparently were not adequately protecting the watershed according to some individuals (Giffard, 1913; Lyon, 1929). The density and type of vegetative cover is important in its influence on the water infiltration process (US Soil Conservation Service, 1972), and it appeared that the monotypic stands of non-indigenous trees were not proving to be an effective watershed management solution.

According to Loumeto and Huttel (1997), there continues to be controversy over whether non-indigenous forest plantations have positive or negative effects on the landscape. Some negative aspects of monotypic tree plantations are that they are associated with decreased levels of biodiversity, adverse effects on soil fertility and stability, displacement of native vegetation (Loumeto and Huttel, 1997), and high consumers of water (Cannell, 1999). Dependent on tree species planted and the success of forest establishment, some researchers have found that forest plantations can increase biological diversity and soil fertility, restore hydrologic functions, and reduce soil erosion (Parrotta, 1992; Parrotta et al., 1997). Lugo (1997), also a proponent of the positive effects of forest plantations reported that, provided the appropriate species is selected for planting, tree plantations can improve soil conditions adding organic matter and nutrients to the soil, and in doing so, decrease the bulk density of an area. Bulk density, a measure of the soil compaction, is one factor influencing rates of infiltration. Typically, low bulk density is associated with high infiltration rates (Rawls et al., 1993). Other soil surface characteristics also influence infiltration, including the amount of litter, density and type of vegetative cover, microtopography, soil type and soil crust formation (Morin and Kosovsky, 1995). If the soil is slow in taking up water, and the rate of precipitation is greater than the rate of infiltration, and surface ponding occurs, Horton overland flow (HOF) may be generated.

Dunne and Leopold (1978) stated that HOF is rare in undisturbed, fully vegetated areas. During my observations of forest plantations in the Wai'anae Mountains, many plantations lack vegetative undergrowth, with only a light to moderate litter layer covering the surface. The observed plantations are not considered examples of fully vegetated, undisturbed forests. On one occasion (November 4, 2001), I personally witnessed HOF occurring as small rivulets in a monotypic *Eucalyptus* plantation in the Wai'anae Mountains, during a short but intense rainfall episode. The Honouliuli Preserve, in the Wai'anae Mountain Range, contains a variety of non-native monotypic forests.

1.3 Honouliuli Background and Overview

The Honouliuli Preserve, the study site for the research, encompasses a large portion of the southeastern slope of the Wai'anae range on O'ahu, Hawai'i. Since 1990, The Nature Conservancy (TNC) has leased the 1,495 ha forest reserve from the Estate of James Campbell (owner since his purchase of the land in 1877) (Frierson, 1973), signing a long-term lease agreement until 2040. The region is comprised of both dry and wet forest habitats ranging in elevation from 366-945 m (The Nature Conservancy, 2000). North of the preserve is Schofield Barracks Military Reservation, south a residential community, the western border is the Wai'anae mountain ridge line with the U.S. Navy communications and storage facility in Lualualei, and bordering the preserve to the east are agricultural lands owned by Del-Monte.

Prior to TNC's lease of the Preserve, the landscape of Honouliuli went through a number of dramatic changes. In the early 1800s, stories were written about the thickly wooded vegetation of the region (Frierson, 1973). However, between 1815-1830, the peak of the sandalwood (*Santalum* spp.) trade began to decimate most of this vegetation. By burning the surrounding vegetation, sandalwood could be detected by the fragrant odor of the smoke. During, or soon after this period, a further and possibly more detrimental onslaught to the region came about from grazing cattle, sheep, goats, and pigs (Judd, 1926). According to Little and Skolmen (1989), in 1924 there were nearly 5,000 head of cattle on the now treeless landscape of the 2,024 ha Honouliuli Ranch. Fortunately, fences erected in 1890 protected some of the native forests, above 457 m, from further grazing (Cuddihy and Stone, 1990).

Giffard (1913) stated:

> As to the Oahu watersheds, more can be said as to what has not been done than otherwise, when it comes to their protection and conservation for water supply. Take the Waianae mountains for instance, their present condition and what they were years ago when the forest extended down the slopes of the valleys and ridges adjacent to the Waialua plains.

Although forest plantings on O'ahu began as early as 1870 (Lubker, 1886; Walker, 1887), mainly by private landowners (Cuddihy and Stone, 1990), the view was that additional effort was needed to decrease soil erosion and runoff by restoring forest cover to the watersheds (Judd, 1926). The greatest planting effort in the Honouliuli Preserve took place between 1934-1941, during which time the Civilian Conservation Corps planted nearly 1.5 million trees, the majority of which were monotypic stands of non-native trees (Little and Skolmen, 1989; The Nature Conservancy, 2000). The goal of C. S. Judd, the Superintendent of Forestry from 1915-1939, however, was to establish not simply forests with tall trees, but forests with thick vegetative understory as well, to absorb the rain that fell to the forest floor (Judd, 1926). A great majority of this intensive planting effort was located in the forest reserves above Honolulu and the eastern slopes of the Wai'anae range (Nelson et al., 1968)

The land was exposed to accelerated soil erosion since the early 1800s, losing the vast majority of its protective vegetation cover to fires, deforestation, and grazing animals. The soils near the base of the preserve have been extensively modified by agricultural activities, while soils in the higher reaches are thin and stony (Cline et al., 1955; Frierson, 1973). Reforested lands, with previously degraded soils, can benefit from tree cover. Soil degradation is defined by the FAO in 1977 as the "result of one or more processes that lessen the current potential capability of a soil to produce, quantitatively and/or qualitatively, goods or services" (Sanchez et al., 1985). Trees introduce roots and can loosen the topsoil and decrease the bulk density, and when these roots decompose, they can increase subsoil porosity thus increasing infiltration rates. Trees can also benefit soil properties by providing shade and litter to lessen both temperature and moisture changes and thus can increase topsoil organic matter content (Sanchez et al., 1985). An increase in organic matter can increase the water holding capacity and cation exchange capacity, and decrease nutrient loss. All of this is dependent on the species planted and it's life cycle phase.

The master plan for the Honouliuli Preserve includes, among other management strategies, habitat restoration, controlling invasive alien plant and animal species, controlling wildfires, and recovering rare species (The Nature Conservancy, 2000). The region is prone to fires due to the little rainfall in this region (Gill, 1989).

1.4 Forest Plantation Species in Hawai'i

Monoculture, as defined by Webster's Third New International Dictionary (Merriam-Webster, 1976), is "the cultivation of a single product to the exclusion of other possible uses of the land". In terms of monotypic tree forests, they are typically exotic species of similar age, planted without the intention of promoting biodiversity. Although these exotic tree plantations provide less biodiversity than native plant communities, if the plantations are planted to cover land previously denuded of native vegetation, they may provide some greater assemblages of biodiversity (Zobel, 1987; Doughty, 2000). In some instances, these monotypic stands will exclude the regeneration of native plants, can invade native forests, and finally can become an invasive 'pest' to the native ecosystem.

Zobel and others (1987) reviewed a number of studies that both supported and opposed the claim that exotic tree plantations use excess water, cause soil deterioration and erosion, and 'poison' other plants (allelopathy). Vegetative growth can greatly influence the chemistry and fertility of the soil, and differs widely among different species (Ewers et el., 1996). Some forest plantation species exhibit allelopathic effects on the surrounding vegetation, or form water-repellent soil surfaces (Doughty, 2000). Allelopathy is defined as "the reputed baneful influence of one living plant upon another due to secretion of toxic substances" (Merriam-Webster, 1976). Water-repellent soil, often referred to as soil hydrophobicity, is a condition in the soil that repels water to some degree (Dekker and Ritsema, 2000), possibly caused from chemicals in the surrounding vegetation. Allelopathy and water repellent soils are not restricted to a single plant species, and research continues to determine which species cause these conditions (Doughty, 2000). Both conditions can presumably affect infiltration rates in a number of ways, contributing to soil erosion and runoff (Kidron et al., 1999; Ritsema and Dekker, 1999).

Chemicals in the plant's roots, leaves, or litter can cause allelopathy, although others have recognized some microorganisms as a source (Zobel et al., 1987). Depending on the spatial extent and severity, allelopathic conditions in a forest plantation can inhibit understory growth. Without understory growth, only the vegetative litter is present to retain soil moisture and reduce the impact of raindrops from detaching soil particles. The root structure of a substantial understory may also improve the water holding capacity and the root channels may provide for higher infiltration rates, reducing soil erosion. Water-repellent soils on the other hand have the obvious effect of increasing the likelihood of overland flow and thus the potential to increase soil erosion.

The monotypic stands found in the majority of planting sites throughout the Honouliuli Preserve are similar to stands found throughout the state of Hawai'i. Due to the diverse topography, soil, and climatic conditions of the islands, roughly 1,100 species were tested and planted in the islands since 1908 (Judd, 1931; Nelson, 1967). The forest plantation species in this particular study are some of those species deemed successful for revegetation, according to Lyon (1929).

1.4.1. Eucalyptus robusta Sm.

Eucalyptus robusta, or robusta eucalyptus and swamp mahogany as it is referred to in Hawai'i, is an evergreen tree native to coastal Queensland and New South Wales, Australia (Wagner et al., 1999). *E. robusta* is a member of the Myrtle family, Myrtaceae, and can reach heights of 24-48 m with a trunk diameter of 0.9-1.2 m. It thrives in regions where annual rainfall exceeds approximately 1,000 mm and at elevations from 152-1,067 m (Little and Skolmen, 1989). *Eucalyptus* is planted in more regions of the world than any other genus of tree (Rhoades and Binkley, 1996), likely due to its rapid growth and ability to adapt in a variety of climates (Buck and Imoto, 1982; Whitesell et al., 1992). In Hawai'i, it has proved successful on poorly drained soils (Schubert and Whitesell, 1985), tolerating waterlogged soils in its natural habitat (Crabb et al., 1981), hence the name swamp mahogany. *E. robusta* was first introduced to Hawai'i around 1885 (Skolmen, 1974) and was the most commonly planted tree in Hawai'i, with nearly 5 million planted before 1960 (Little and Skolmen, 1989) now covering over 8,100 ha in the state (Buck and Imoto, 1982).

Native eucalypt forests in Australia are well known for their ability to control erosion, however, introduced eucalypt plantations have been known to cause negative impacts on the land. Doughty (2000) reviewed previous work that suggested these plantations do not inhibit but rather promote soil erosion. Although the leaves of eucalypts intercept between 10-25 % of precipitation, runoff and erosion can range from minimal to substantial depending on the soil and vegetation type, and the degree of slope (Doughty, 2000). *Eucalyptus* is considered allelopathic to other plants (Poore and Fries, 1985), likely contributing to the lack of understory in most plantations of this species.

Giffard (1913), referring specifically to the forests of Hawai'i, believed that reforestation efforts utilizing *Eucalyptus* should be abandoned if the purpose of planting was for watershed protection. Giffard, as well as others (Lyon, 1929) felt that this genus provided little vegetative understory crucial to erosion control and water conservation. In addition, he viewed these trees as consuming a greater amount of water than other species and thus not beneficial to the purpose of water conservation. Poore and Fries (1985) summarized a number of studies in reference to the ecological effects of *Eucalyptus* and found no conclusive evidence to support this widely held idea that eucalypts use significantly more water than other hardwoods. They also found no evidence to support the idea that these forest plantations deteriorated soil properties (Sanchez et al., 1985) or caused irreversible site damage as others have suggested. Poore and Fries (1985) did conclude, however, by stating that in drier climates, eucalypts are a poor choice for erosion control, and thus the situation in question is dependent on the climatic conditions at the site.

Although reforestation efforts in Hawai'i originally focused on watershed protection and supplying fuelwood and fence posts for the sugar plantations, the focus of these efforts began to shift slightly in the1940s towards watershed protection and timber harvesting (Cuddihy and Stone, 1990). Eucalypts are among one of the fastest growing producers of wood in the world (Doughty, 2000) and with *E. robusta* covering a vast majority of forest reserve land in Hawai'i, it was a natural choice among many in the timber industry. By the 1960s, *E. robusta* and *Fraxinus uhdei*, among many other fast growing hardwoods, were planted extensively on forest reserve land as potential timber species (Cuddihy and Stone, 1990). Although *E. robusta* was considered excellent timber (Bryan, 1957), *E. saligna* soon became the preferred timber species of *Eucalyptus* and *F. uhdei* proved unsuccessful for timber harvesting (Little and Skolmen, 1989). Currently, the timber industry has not materialized into what was imagined decades ago.

1.4.2. Fraxinus uhdei (Wenzig) Lingelsh

Fraxinus uhdei, commonly known as tropical or Mexican ash, is a deciduous tree native to western and southern Mexico (Wagner et al., 1999). *F. uhdei* is a member of the olive family, Oleaceae, reaching heights of 24 m with a trunk diameter of 0.9 m. It is a shade tolerant tree when young and regenerates well in moist regions. Two trees of this species *F. uhdei* were introduced to the Hawaiian Islands in the late 1800s and subsequently became the seed source for nearly every planting on the islands. The trees were initially introduced as shade trees (Little and Skolmen, 1989), however, when it was apparent that they adapted well to adverse conditions and grew rapidly, the trees were utilized as forest plantation species for watershed protection (Whitesell et al., 1971). Plantings of this species by the Division of Forestry began around 1920 and to date have planted over 700,000 trees throughout the state (Little and Skolmen, 1989). During the 1960s, *F. uhdei* was considered a potential timber species, much like that of *E. robusta*. However, it was soon evident that this species was not adequately suited for the timber industry because of undesirable splitting and forking characteristics and thus further plantings were curtailed (Burgan, 1971; Walters and Wick, 1973).

F. uhdei is considered a pest on both Moloka'i and O'ahu (Smith, 1985), and an invasive species to disturbed native forests (Ares and Fownes, 2000). It is considered among the 86 worst plant invaders in Hawai'i, in non-urban and uncultivated regions, because it can form single species stands. One of the most extensive infestations of this species is located along the Honouliuli trail in the Wai'anae Mountain Range, O'ahu, Hawai'i (Smith, 1985).

F. uhdei is winter-deciduous in Hawai'i shedding its leaves every year, however, there is only a light litter layer due to its rapid rate of decomposition (Harrington and Ewel, 1997). Although *F. uhdei* is deciduous, it can still provide an extensive canopy that may prevent the understory growth of shade intolerant species (Ares and Fownes, 2001).

1.4.3 Acacia confusa Merrill

Acacia confusa, also known as formosan (Smith, 1985) or formosa koa, is an evergreen tree native to Taiwan and the Philippines. *A. confusa* is a member of the pea family, Fabaceae, reaching to heights of 6-15 m with a trunk diameter of 0.3 m (Wagner et al., 1999). It grows well in wet and dry regions of the islands from sea level to 610 m (Little and Skolmen, 1989). Introduced to Hawai'i from Taiwan around 1915 by the

Board of Agriculture and Forestry and the Hawaiian Sugar Planters' Association (Degener, 1937), *A. confusa* was used in ornamental and forest plantings for revegetating eroded sites. Similar to both *Eucalyptus* and *Fraxinus*, *Acacia* also adapts well to dry, adverse conditions and thus has been planted extensively for revegetation purposes (Smith, 1985). *A. confusa* grows well in compacted soil, enabling roots to absorb water from deep soil layers when the surface soil dries (Liang et al., 1999). However, *A. confusa* was never considered a potential timber species due to the small size and the crooked branches of this particular species. The Division of Forestry has planted over 295,000 trees of this species on all the main Hawaiian Islands (Little and Skolmen, 1989), with others established by means of aerial broadcasting (Smith, 1985). Aerial seeding began in 1929, using a variety of mixed exotic seeds (Skolmen, N.D.).

A. confusa is considered a pest species on the islands of O'ahu and Maui in addition to being apparently allelopathic. The understory of these plantations are typically barren and are considered fire resistant due to the difficulty in fire spreading underneath, due to the lack of understory (Smith, 1985).

1.5 Soil Hydro-Physical Properties

In the late 1800s, Schuyler and Allardt (1889) recognized that during intense rainfall, infiltration rates are low and runoff is high in mountainous regions denuded of vegetation on O'ahu, Hawai'i.

> The infiltration would be much greater than it is if the rainfall came in gentle showers, evenly distributed through the year, but whenever storms occur in which the precipitation exceeds one or two inches in 24 hours, absorption cannot take up the water as fast as it comes, and the excess finds its way rapidly into the streams and flows away.

Schuyler and Allardt are describing a process similar to a theory set forth by R.E. Horton (1933), which proposed that overland flow will result when the rainfall intensity over an extended period of time is greater than the infiltration capacity of the soil surface. This mechanism, the Horton overland flow (HOF), can increase the amount of overland flow in regions where vegetation has been removed or soil compaction increased (Ziegler and Giambelluca, 1997; 1998). The region Schuyler and Allardt describe as being witness to overland flow events is the Wai'anae Mountains, covered during that time mainly with low lying grasses, denuded of forest cover by ungulate overgrazing.

Infiltration is defined as "the movement of water into the soil," and can be measured as a rate, in units of depth per time (Dunne and Leopold, 1978). Infiltration can further be described as "the process of water entry into the soil through the soil surface"; the important distinction here is the soil surface (Ward and Robinson, 1990). During periods of precipitation, most of the water is absorbed at the soil surface layer. Most soils are hydrophilic, and thus water penetrates easily through the soil surface by gravity and capillary forces (Doerr et al., 1996). There is a maximum limit and rate, however, at which a particular soil can absorb this water influx (Dunne and Leopold, 1978) and is recognized as the infiltration capacity of the soil. Horton considered that the infiltration capacity was controlled mainly by processes occurring at the soil surface (Ward and Robinson, 1990).

The infiltration rate is extremely important to the hydrology of a region, because it affects the amount of surface runoff that can be generated and consequently the extent of soil erosion possible (Viessman et al., 1972; Ward and Robinson, 1990). The infiltration rate is influenced by a number of factors, including type and amount of vegetative cover and litter, temperature, rainfall intensity, physical properties of the soil, soil surface crust, organic matter content (Viessman et al., 1972), and water-repellency of the soil or lack or it (DeBano, 1969a; DeBano, 1969b).

Vegetative cover will typically provide protection from the impact of rainfall on the soil below, reducing soil erosion. However, this is dependent on the density of ground cover and the height and continuity of the canopy (Morgan, 1995). Ruangpanit (1985) determined that there should be a minimum of 70% canopy cover combined with minimal bare soil surface to decrease surface runoff. His research also suggested that a protective litter layer and high organic matter help to preserve the soil moisture, thereby increasing the rate of infiltration and decreasing runoff and erosion.

A number of studies have investigated the effects of vegetation on infiltration rates. Tromble et al. (1974) stated that the vegetative cover and condition of the soil surface were key factors in determining infiltration. Dunne et al. (1991) and Burk et al. (1999) stated that roots, microfauna, and organic matter can increase infiltration rates and vegetative cover can also intercept energy from raindrops and prevent soil surface sealing that lowers infiltration rates. The litter layer and surface vegetation help to filter the splashed soil particles from raindrops, preventing the clogging of soil pores, and increasing infiltration rates (Wiersum, 1985). However, Deuchars et al. (1999) reported that even if the species of a revegetated forest returned to its natural state, if land disturbance was excessive, for instance over grazing by animals creating soil compaction, infiltration rates of a forest soil might not return to their normal state.

Yamamoto (1963) and Wood (1971) examined this idea of soil compaction affecting infiltration rates in Hawai'i. Yamamoto's study determined that forest soils had some of the lowest average bulk densities when compared to pasture and cultivated soils (Yamamoto, 1963). Wood (1971) determined that bulk density directly influenced infiltration and conductivity rates. In 1977, Wood found lower bulk densities, greater porosities, and higher infiltration rates in forest covered soils than in nonforested (pasture and agriculture) soils (Wood, 1977). Saturated hydraulic conductivity (K_s) is considered a useful method to determine the benefits of revegetation, according to Ziegler and Giambelluca (1998). Vegetation also influences soil moisture variability, a factor in calculating K_s. Water moves through the soil as either unsaturated or saturated flow. Saturated flow occurs when the entire pore space is occupied by water and flows in response to a difference in the hydraulic gradient (DeBano, 1969).

Famiglietti et al. (1998) reported that vegetation affects the soil hydraulic conductivity through root activity and the addition of organic matter to the soil surface layer. Evans (1980) earlier stated that organic matter is important because of its influence on aggregate stability. Lower soil organic matter content is generally associated with an increased rate of erodibility. As the leaf litter decomposes, it increases the humus content in the topsoil and provides ideal conditions for increased water permeability and aggregate stability (Wiersum, 1985).

Wood (1971, 1977) examined hydrological differences between ungrazed forest plantations, agriculture, and pasture soils in Hawai'i and concluded that infiltration rates were highest in forested sites and were associated with lower bulk densities and greater porosities in the forest covered soils. Wood also revealed one interesting characteristic, a non-wettable or water-repellent soil under an *E. globulus* forest type. This one site recorded lower infiltration rates than a pasture site of similar soil series.

Larson and Pierce (1991) identified several key soil properties to assess soil quality, such as, but not limited to - infiltration rates, bulk density, and organic matter content. Although Karlen et al. (1997) and Seybold et al. (1997) agree that these key soil properties are important in determining soil function, they disagree with the concept of soil 'quality' and that a specific definition of soil 'quality' can be applied to any soil type. Rather, their suggestion is that a definition of soil 'function', rather than 'quality' can be applied to a soil.

My study investigates how certain soil properties are functioning under forest cover and how this compares with grassland sites, similar to the denuded region prior to forest plantings. This study will assess the functional changes that may have occurred over time with respect to the infiltration rates in specific soil types and specific plantation species.

1.6 Need For This Research

At one time, the region where the Honouliuli Preserve now resides, was a watershed that maintained high infiltration rates with a low susceptibility to erosion (The Nature Conservancy, 2000). Are regions of the Preserve continuing to function in this manner today? Yamamoto and Anderson (1967) investigated erosive characteristics of some soils in the Wai'anae Mountains, and found that some of the non-native forest plantation species were more effective in reducing the susceptibility of soil to erosion than native forest cover. In summary, however, they indicate that without any vegetative cover the soils of the Wai'anae Range are 'highly erodible'.

Prior to this study, data were insufficient to determine whether reforestation efforts in the Wai'anae Range had a significant effect on soil hydrologic characteristics. Although I cannot replicate the exact conditions prior to the reforestation efforts, I did choose control sites in an attempt to represent some of the attributes of that time. The research represented here was conducted to answer the question: Has the planting of non-native monotypic forests on a previously denuded landscape significantly altered or affected the infiltration rates, in addition to affecting some of the physical and chemical characteristics of the soil, within certain species in the Honouliuli Preserve?

Chapter 2. Methodology

2.1 Research Strategy

The research strategy was to measure infiltration rates under different forest stands and then to compare these rates to areas not involved in the revegetation effort. To study the effects monotypic, non-native forest plantations have on soil infiltration rates in the Honouliuli Preserve, measurements were taken to determine saturated hydraulic conductivity (K_s), sorptivity (S), bulk density (ρ_b), and organic matter content (LOI). Selection of the forest plantation plots was based on: species planted extensively on the Hawaiian Islands; relatively monotypic stands; and species associated with some negative aspect regarding the revegetation effort. Four forested study plots were selected, two *Eucalyptus robusta* (swamp mahogany) plots, one *Fraxinus uhdei* (tropical ash) plot, and one *Acacia confusa* (formosan koa) plot (Figure 1). In addition, two control plots were selected based on soil type and similarity in vegetative cover.

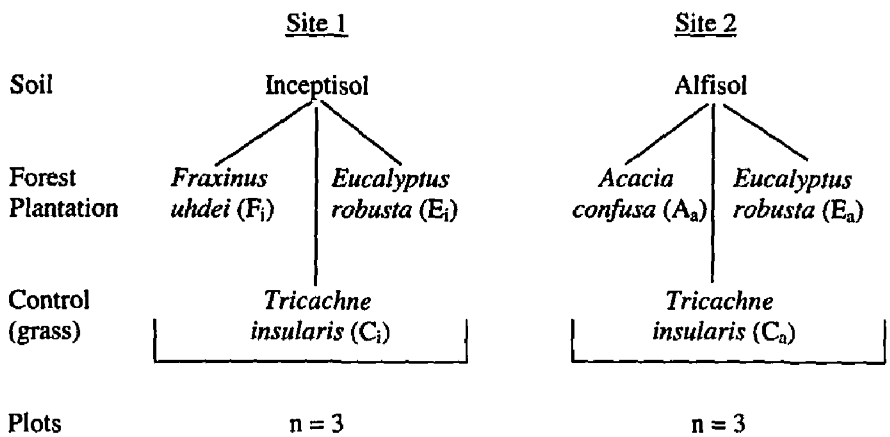

Figure 1. Experimental design of study sites.

2.2 Study Area

The study sites are located in O'ahu, Hawai'i, on the east facing slope of the Wai'anae Mountain Range, in the Honouliuli Preserve as well as sites that border the Preserve (Fig. 2). Protected by The Nature Conservancy since 1990, this 1,495 ha preserve contains a variety of monocultural stands. The forested study plots are located within the Honouliuli Preserve and the control plots are located on private lands outside of the Preserve at the base of the Wai'anae Mountains.

The two control plots are non-forested areas covered by introduced grass species (*Tricachne insularis* – sour grass). Grasses are typically some of the most destructive and widespread of plant invasions (D'Antonio et al., 1998) and are probably representative of the vegetative cover prior to the massive planting efforts. There are no available records or visible signs that these areas were ever included in any of the re-vegetation efforts that took place within the Preserve and planted with forest species. The control plots are former agricultural lands previously planted with pineapple and/or sugar cane (The Nature Conservancy, 2000), and aerial photos from 1972 show agriculture crops planted in these areas (Sahara et al., 1972). Due to a lack of detailed records, it is difficult to assess how far the cultivated lands extended into the Preserve, prior to the forest plantings, but there is evidence in all of the forested study plots of furrowed land, indicating cultivation at some point.

The study sites are grouped according to two different soil types. The soil series mahana, an inceptisol (Foote et al., 1972), includes one *E. robusta* plot, one *F. uhdei* plot, and one control plot. The soil series kemoo, an alfisol (Foote et al, 1972), includes one *E.*

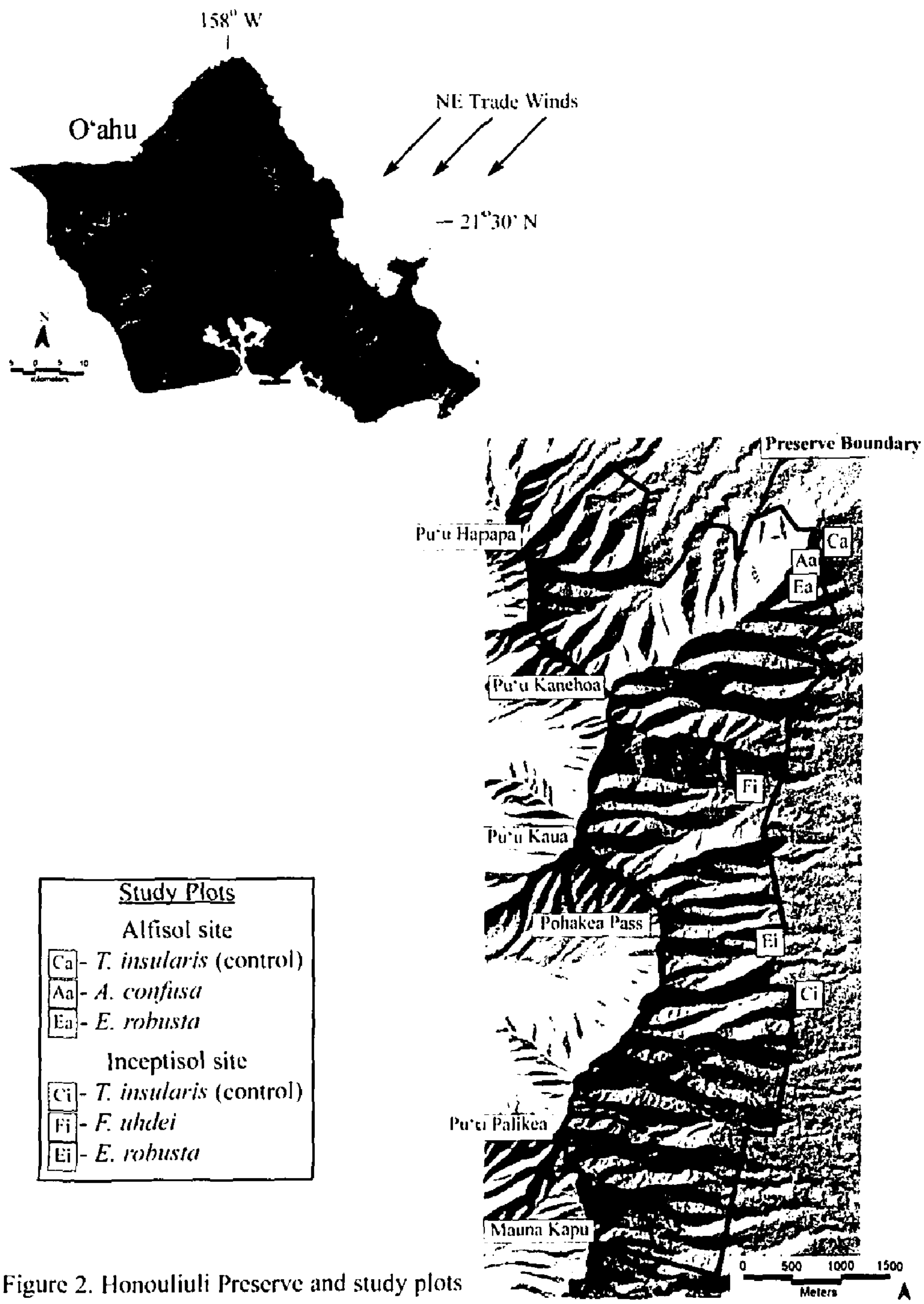

Figure 2. Honouliuli Preserve and study plots

robusta plot, one *A. confusa* plot, and one control plot. Table 1 describes the characteristics of the two study sites with three plots per site.

Table 1
Site characteristics of study plots.

Vegetative Cover	Soil Series/Order*	Elevation (m)	Area (ha)	Mean Annual Rainfall (mm)†	Slope (°)	Litter (%)
A. confusa	Kemoo/ Alfisol	425-455	5.0	1100-1200	5-30	80-90
E. robusta		455-485	1.3‡		10-30	60-70
T. insularis (Control)		415	1.0		0-15	20-30
F. uhdei	Mahana/ Inceptisol	425	1.0‡	1000-1100	0-20	60-70
E. robusta		365-395	3.6‡		5-35	60-70
T. insularis (Control)		335-365	1.2		5-15	20-30

* Foote et al. (1972)
† *Giambelluca et al. (1986)*
‡ J. Garrison, University of Hawai'i Dept. Botany, pers. comm., 2003

The geographic setting of the Hawaiian Islands presents some unique climatic conditions for the Honouliuli Preserve. There is a high spatial variability of rainfall in the islands due to a combination of factors, including the northeast trade winds ('trades') that bring the majority of annual rainfall, orographic effects of the high mountain ranges and dramatic elevation changes. The Wai'anae Mountains run roughly perpendicular to the trades and lie downwind (during trades) from the Ko'olau Mountains, which also run approximately perpendicular to the trades. This condition creates a rainshadow effect on the Wai'anae Mountains, with the windward side of the Wai'anaes receiving substantially less precipitation than the Ko'olaus. The mean annual rainfall for the Honouliuli Preserve ranges from 800-1400 mm/yr (Giambelluca et al., 1986). However, 1 h duration rainfalls with a 2 yr return period have recorded upwards of 38 mm/h and over a 10 yr return period 51 mm/h (Giambelluca et al., 1984).

2.2.1 *Soils of Honouliuli Study Sites*

Roughly 80-90 % of the soils in the Honouliuli Preserve are classified as Tropohumults-Dystrandepts Association, which cover the steep slopes of the Wai'anae Mountains. Two soil types were examined during this study. Within and bordering the middle region of the Honouliuli Preserve, are located three of the study plots for the soil order inceptisols (Figure 1). Inceptisols are typically young soils, although not necessarily recent, and represent roughly one-fourth of all the land area in the state (Foote et al., 1972; McCall, 1975). Within the inceptisols, is the suborder andepts that developed in volcanic ash and are well-drained lightweight soils (McCall, 1975). Further classification of the soil is the series mahana. Mahana soils are dusky-red in appearance and developed in old, highly weathered volcanic ash. They contain higher bulk densities than most soils derived from volcanic ash (Foote et al., 1972).

In the northern region of the Preserve, the remaining three study plots are located in the soil order alfisols and make-up less than 1% of the soils in Hawai'i. However, the majority of this soil is located within the Preserve. These soils are further classified in the suborder ustalfs, the only suborder for alfisols in Hawai'i. Within the ustalfs is the soil series kemoo, distinguished by the very dusky red to dark reddish brown appearance. (Foote el al., 1972).

2.2.2 *Vegetation*

Eucalyptus robusta Sm.

Two *E. robusta* plots were investigated in this study, one located on an alfisol and the other on the inceptisol. The *E. robusta* trees in the alfisol soil create a relatively open canopy, as the trees are discontinuous with roughly a 40% mix of other tree species

(T. Restom, University Hawai'i Dept. Botany, pers. comm., 2003). The trees in this site have a mean height of 9 m (J. Garrison, pers. comm.). The vegetative litter contains roughly 60-70 % of coarse vegetative matter, consisting of leaves, twigs, and large branches. The vegetative litter ranges from bare regions to deep layers over 10 cm thick, apparently where litter has accumulated by wind or overland flow (personal witness to rainstorm event in November 2000 creating overland flow).

E. robusta located on inceptisols consist of much larger specimens, with a mean height of 20.7 m (J. Garrison, pers. comm.), spaced evenly and much further apart, and the canopy is more continuous, than the other *Eucalyptus* plot. The plot contains a mix of less than 10% other tree species (T. Restom, pers. comm.). The plot also contains roughly 60-70 % vegetative litter coverage with coarse vegetative matter.

Fraxinus uhdei (Wenzig) Lingelsh

The *Fraxinus uhdei* plot consists of trees with a mean height of 7.7 m (J. Garrison, pers. comm.) and a dense canopy cover, even though the species is considered deciduous. There is less than a 30% mix of other tree species (T. Restom, pers. comm.) and 60-70 % of the soil is covered with vegetative litter and contains mainly highly decomposed vegetative matter.

Acacia confusa Merrill

The *Acacia confusa* plot contains species with heights of 3-5 m. The plot is moderately dense, with many stages of *Acacia* growth, not evenly distributed, and with less than a 5% mix of other tree species. There is roughly 80-90 % litter layer coverage and is fairly evenly distributed over the plantation, with few bare spots, and consists of both coarse vegetative matter and decomposed vegetation.

Tricachne insularis (L.) Nees

Within the control plots is the species *Tricachne insularis*, a member of the grass family, Poaceae, also known as sour grass and often referenced as *Digitaria insularis* (L.) Mez ex Ekman. It is native to the Neotropics and widely naturalized in the Pacific islands. In Hawai'i, it is found in disturbed sites and abandoned fields on all the main islands except Ni'ihau, ranging in elevation from 0-340 m. The grass can reach heights of 100-150 cm (Wagner et al., 1999), the approximate height of the grass in both study control plots. Within the control plots, the grass grows in clumps with roughly 85-90 % coverage of the areas and with soil between the clumps covered with a 20-30 % litter layer.

2.3 Sampling Strategy

Soil data were collected between 2000-2002, during the months November through July. A minimum of 30 measurements were made within each of the six plots. In all but one of the study plots (*T. insularis* – control in inceptisol), some of the samples were not utilized in the final analysis because of errors made either in the field or laboratory stage or due to sampling limitations. Therefore, the number of samples analyzed varied for each particular site and each particular soil attribute (Table 2). Figure 3 displays the instruments utilized in the field for this study.

Table 2
Total number of study plot measurements.

	Number of measurements			
	K_s	$\rho_{b\,90}$*	$\rho_{b\,top\,45}$†	LOI
<u>Site 1 (Inceptisol)</u>				
F. uhdei (F_i)	35	38	38	36
E. robusta (E_i)	26	32	32	32
T. insularis (C_i)	32	32	32	32
<u>Site 2 (Alfisol)</u>				
A. confusa (A_a)	31	32	32	32
E. robusta (E_a)	35	36	36	36
T. insularis (C_a)	29	32	32	32
Totals	188	202	202	200

*bulk density from 90 cm^3 core sample
† bulk density from top 45 cm^3 core sample

2.3.1 Gravimetric Soil Moisture

The soil samples were massed using the Scientific 5200 balance to determine the initial moisture content, then dried in the Fisher Isotemp 630 oven at a constant temperature of 105°C for at least 48 h. Once drying was complete, the samples were re-massed to obtain the dry mass of the sample. A temperature of 105° C has been used as a standard to evaporate water from soil samples, a temperature low enough to prevent the burning off of organic matter yet high enough to remove the water in the soil. Typically, 24 hours is used as the time for drying soil samples, however, my samples were dried at 105°C for 48 h because it was apparent that additional drying time was needed to achieve constant mass. The data from the massed samples were then entered into StatView 4.5 (SAS, 1999) to compute K_s, θ_0, θ_n, $\rho_{b\,90}$, $\rho_{b\,top\,45}$, $\rho_{b\,bottom\,45}$, and LOI.

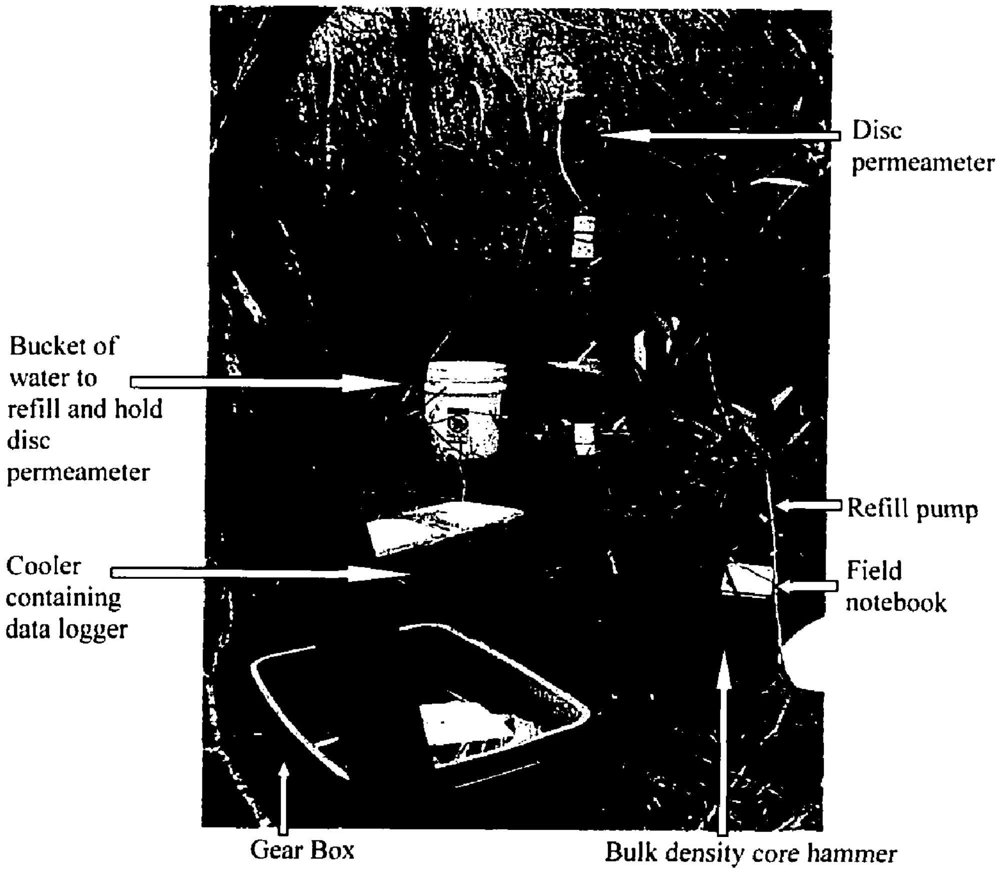

Figure 3. Field instruments and layout in *Acacia confusa* (A_a) plot.

2.3.2 Saturated Hydraulic Conductivity and Sorptivity Measurements

Ziegler and Giambelluca (1998) considered saturated hydraulic conductivity as "a useful index for assessing benefits of revegetation because K_s largely controls the infiltration of rainwater." There are two soil properties that control the flow of water, the hydraulic conductivity K_s, accounting for the effects of gravity, and sorptivity (S) or the capillary action (Angulo-Jaramillo et al., 2000).

A disk permeameter fixed with a pressure transducer was used to measure K_s (Vadose Zone Equipment Corporation, Amarillo, TX). Data were recorded with a Campbell Scientific, Inc. (Logan, UT) 21x data logger at 1 s sampling intervals . The equation (1) for calculating K_s is defined as (Perroux and White, 1988; White et al., 1992):

$$K_s = I - 4bS^2 / \pi r(\theta_0 - \theta_n) \qquad (1)$$

where θ_n is the volumetric moisture content of the 'dry' in situ soil (cm^3), θ_0 is the volumetric water content of the 'wet' in situ soil (cm^3), r is the radius of the base of the permeameter (cm), b is a constant set at 0.55, S is the sorptivity ($L\ T^{-1/2}$) obtained by plotting cumulative infiltration versus the square root of time near the start of infiltration (Figure 4), and I is the infiltration rate ($L\ T^{-1}$) (Figure 5) calculated as:

$$I = q / \pi r^2 \qquad (2)$$

where q ($L^3\ T^{-1}$) is the slope of the plot of cumulative flow volume versus time, after the flow rate has reached steady-state, and r is as before.

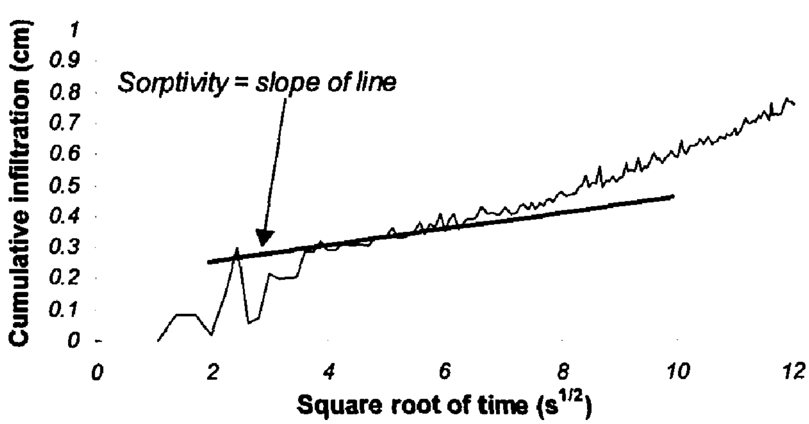

Figure 4. Graphical representation of the sorptivity curve. Example from F_i measurement #3 ($S = 4.08E\text{-}04\ m/s^{1/2}$)

Perroux and White (1988) demonstrated that the disk permeameter is a useful tool to measure soil hydrologic properties in the field. The disk permeameter requires a near-level surface to function properly. Sullivan et al. (1996) have suggested cutting a 'bench' into the hillside to create level sites, however, research into the usefulness of disk permeameters on sloping lands does not consider creating a 'bench' a necessity (Joel and Messing, 2000). For the research conducted here, infiltration properties can only be measured if the soil surface layer is not disturbed and thus a bench was not cut into the hillside for any of the measurements.

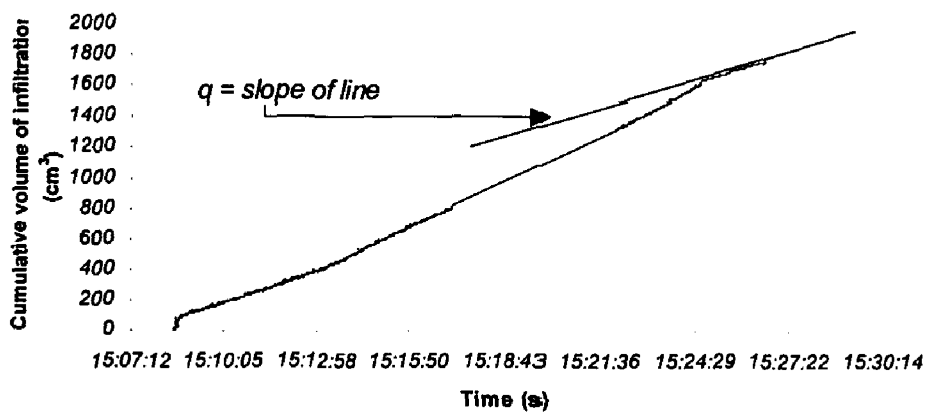

Figure 5. Graphical representation of the steady state flow rate. Example from F_i measurement #6 (K_s = 186.7 mm/h)

At each sampling site, the permeameters were always placed at a distance > 3 m from all other sampling sites. Once a near-level site was located, the site typically required some minimal preparation. To prepare the sampling site, methods similar to Ziegler and Giambelluca (1997) were followed. All visible vegetation (grasses, above ground roots, and litter) was removed or cut away from the sites. Next, a fine layer of dry capping sand was placed on the site to level the surface and to act as a contact or seal between the permeameter and soil (Sullivan et al., 1996; Ziegler and Giambelluca, 1997). Excess sand was removed from the outside of the ring to prevent water from flowing horizontally at the point of contact with the permeameter. The high conductivity of sand makes it an ideal contact between soil surface and permeameter because the influence of sand can usually be neglected in determining the steady-state flux (Angulo-Jaramillo et al., 2000; Minasny and McBratney, 2000).

The data logger records water volume changes within the permeameter immediately upon the disk contacting the sand surface. Measurements are taken at 1 s time intervals for the first 2-3 min. Once the permeameter achieves a steady-state of infiltration, determined by visual inspection of air bubbles moving steadily up the permeameter column, the operator reactivates the data logger, which begins recording again every second for 3 min. Following the immediate removal of the permeameter, the sand was moved aside and a small soil sample (top 1 cm) was removed and placed in a labeled zip lock bag. This soil sample was used to calculate the ending gravimetric soil moisture content (θ_0) and used as a factor in calculating K_s. The equation for calculating θ_0 is:

$$\theta_0 = (M_w - M_d) / M_d * \rho_b \qquad (3)$$

where M_w is pre-oven dried soil mass, M_d is the oven dried (105° C) soil mass, and ρ_b is the dry bulk density from a 45 cm^3 soil core.

The data from the beginning steady-state infiltration rate is used to estimate the sorptivity (S) (Simunek et al., 1999). When infiltration rates are dominated by capillary forces in the soil (Cook and Broeren, 1994; Angulo-Jaramillo et al., 2000) and not by gravity (Bonsu, 1993) sorptivity can be measured. Sorptivity is dependent on the initial water content of the soil and therefore needs to be measured (Bonsu, 1993).

To measure the initial gravimetric soil moisture content (θ_n), a small soil sample is taken near where the permeameter is located. This involves scrapping the top 1 cm of soil and placing it in a labeled zip lock bag. The equation for calculating θ_n from is:

$$\theta_n = (M_w - M_d) / M_d * \rho_b \tag{4}$$

2.3.3 Bulk Density

Larson and Clapp (1984) consider soil compaction as one of the most important factors influencing soil processes. Soil porosity changes with an increase or decrease in soil compaction (Brandt, 1969), influencing infiltration rates. Bulk density is defined as the ratio of the mass of dry solids to the bulk volume of the soil. Typically, as bulk density increases, saturated hydraulic conductivity decreases (Rawls et al., 1993), and thus becomes an influential factor in measuring infiltration rates. To measure the soil bulk density, two soil core samples at each permeameter site were taken with an AMS bulk density corer, this is a double cylinder hammer driven 90 cm^3 core sampler, sampling the upper 5 cm of the soil. The samples were taken far enough from the permeameter so as not to affect the K_s readings and were not located where the initial gravimetric soil moisture content sample was removed. One of the two 90 cm^3 core samples taken is divided into two 45 cm^3 cores and the other is an intact 90 cm^3 core. The top portion of the 45 cm^3 core is used to measure the bulk density of the upper 2.5 cm of soil surface and the bottom portion of the 45 cm^3 core was used to measure the bulk density 2.5-5 cm below the soil surface. Both of the upper and lower samples were taken to distinguish and characterize the vertical compaction within each site. All samples were placed into labeled zip lock bags. The equation for calculating the bulk density of the 90 cm^3 core sample ($\rho_{b\,90}$) is:

$$\rho_{b\,90} = \text{oven dry mass (g)} / \text{cylinder volume } (cm^3) \tag{5}$$

The 90 cm^3 core and top 45 cm^3 core samples can also be used to measure θ_n at each sampling site, although these measurements are integrated over a greater depth. The equations for calculating θ_n from the 90 cm^3 core sample ($\theta_{n\,90}$) is:

$$\theta_{n\,90} = (M_{w\,90} - M_{d\,90}) / 90 \tag{6}$$

2.3.4 Loss-on-ignition

An index of soil organic matter was determined for each of the top 45 cm^3 core samples using low temperature loss-on-ignition (LOI). Organic matter can improve the physical properties of the soil (Nakaya and Motomura, 1984). Organic matter, apart from improving soil cohesiveness and maintaining a high water-holding capacity, can also influence the bulk density of the soil (Larson and Clapp, 1984; Morgan, 1995), and thus can be considered an important element in assessing soil quality. An increase in the soil organic matter will increase the porosity of the soil, increasing infiltration rates (Nakaya and Motomura, 1984).

The procedure for LOI follows that of Rhodes et al. (1981) and Ben-Dor and Bannin (1989). The procedure requires that all visible organic matter be removed from the sample. Then, 50 - 100 g of the remaining sample is crushed in a mortar with a pestle until it can pass through a 2 mm sieve. Approximately 5 g is transferred to a crucible and placed in a drying oven set at 105° C for at least 48 h. Once the initial drying process is complete, the sample is placed in a desiccator for a minimum of 20 min. The mass of the sample is recorded (M_{105}) and placed in the NEY M-525 muffle furnace at a temperature of 400° C for 8-16 h. The sample is removed and placed in a desiccator for a minimum of 30 min. The mass is again recorded (M_{400}). The following equation is used to compute an index of the percentage of organic matter:

$$LOI = [(M_{105} - M_{400}) / M_{105}] * 100 \qquad (10)$$

All soil samples were processed in the Geography Department's Geomorphology Laboratory, at the University of Hawai'i at Mānoa.

2.4 Statistical Analysis

Data were entered into Microsoft Excel (version 97) and explored using StatView 4.5. The specific questions being asked, with regards to differences and correlations between specific variables, required separate statistical tests to be carried out. Depending on the data set, some transformations (log or squared) were required to conduct parametric tests, such as, unpaired means test and one-way analysis of variance (ANOVA) followed by Fisher's PLSD post –hoc test. However, the majority of the data required the use of nonparametric testing, such as, Mann-Whitney U test, Kruskal-Wallis test, and the Spearman rank correlation test.

In all cases, p-values were compared to a threshold alpha (α) value of 0.05 or 5%. The p-value, also known as the probability value, and its relationship to the α value provides evidence to either accept or reject a null hypothesis. In this case, the null hypothesis means that there is either no significant difference or correlation within the data set examined. The smaller the p-value, the stronger the evidence there is to reject the null hypothesis and accept the alternate hypothesis. If the p-value is less than 0.05, evidence suggests that the null hypothesis can be rejected with a 95% confidence level.

To evaluate the relationship between two variables, the correlation coefficient (r) was obtained. The Spearman rank correlation was used, which, as the name implies, is based on ranking the data, a method that resists outliers. The Spearman rank correlation coefficient is applied to variables with a monotonic or linear relationship (SAS, 1999).

Sobieraj et al. (2002) used box plots to graphically illustrate differences, as well as variability within their hydraulic conductivity data. Elsenbeer et al. (1992) provided a spatial analysis of soil hydraulic conductivity in a tropical rainforest catchment utilizing box plots in their final analysis. I have also included box plots in my results section (Chapter 3) to offer a quick visual image of the data, comparing the distribution of the variables. The type of box plot used here displays notches to represent a 95% confidence interval for the median (SAS, 1999) (Figure 6).

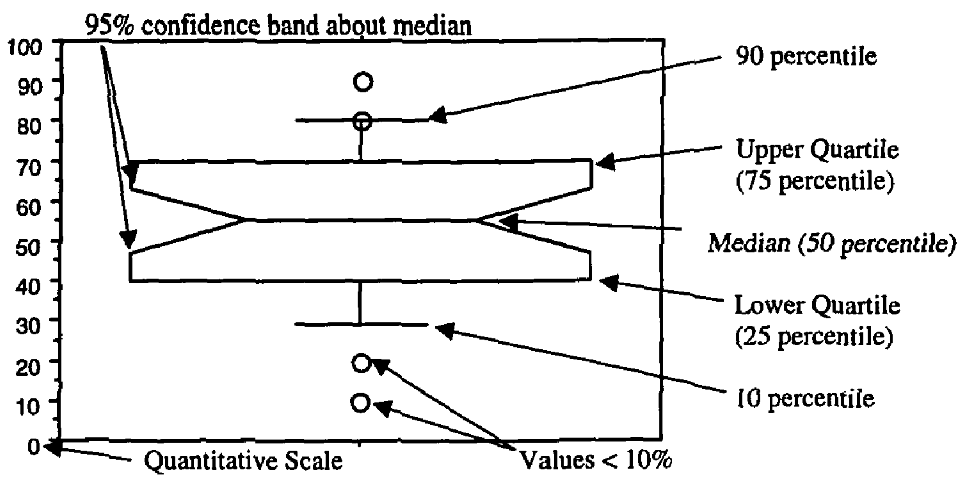

Figure 6. Notched box plot overview

Chapter 3. Results and Discussion

This study consists of two control plots, similar in nearly every aspect with the exception of soil type – alfisol versus inceptisol. With soil type being the single difference, it was then possible to infer that if saturated hydraulic conductivity (K_s) values were significantly different, then soil type could be a control on K_s. Therefore, if differences between the control plots are statistically significant, then direct comparisons could not be made between plantation species. In addition to measuring K_s, it was also necessary to measure factors that influence infiltration rates, such as ρ_b and LOI. These physical and chemical soil characteristics can greatly affect soil hydrologic properties, as mentioned previously, and thus their correlations to K_s values are important. Thus, significant differences and correlations of these influential factors were explored in reference to K_s as well as to one another.

3.1 *T. insularis* (sour grass) - Control versus Control

3.1.1 Saturated Hydraulic Conductivity (K_s)

The mean K_s value for the control site located in the inceptisol soil type (designated C_i) is 72 mm/h with a standard deviation of 52 mm/h (Table 3; in addition, see Appendix A for a summary of all K_s values). The mean K_s value for the control site located in the alfisol soil type (designated C_a) is 277 mm/h with a standard deviation of 157 mm/h.

Table 3
Descriptive statistics for the two control plots – *T. insularis* (sour grass)

Control areas n	(C_i) 32	(C_a) 29 - 32*
K_s (mm/h)		
Mean	71.6	276.8
Std. Dev.	51.8	156.6
Median	53.9	263.2
MAD†	39.3	91.1
Min & Max	1.1 - 174.1	64 - 776.3
$\rho_{b\,90}$ (g/cm^3)		
Mean	0.876	1.052
Std. Dev.	0.085	0.124
Median	0.893	1.054
MAD	0.050	0.104
Min & Max	0.685 - 1.04	0.871 - 1.373
$\rho_{b\ top\ 45}$ (g/cm^3)		
Mean	0.824	0.993
Std. Dev.	0.119	0.091
Median	0.851	0.991
MAD	0.056	0.054
Min & Max	0.441 - 1.034	0.791 - 1.164
$\rho_{b\ bottom\ 45}$ (g/cm^3)		
Mean	0.949	1.153
Std. Dev.	0.100	0.109
Median	0.944	1.142
MAD	0.064	0.054
Min & Max	0.664 - 1.178	0.990 - 1.510
LOI (%)		
Mean	18.7	16.0
Std. Dev.	3.3	2.4
Median	18.9	15.9
MAD	1.7	1.7
Min & Max	13.5 - 29.2	11.0 - 20.0

*The number of samples for K_s was 29 and for all other measurements a total of 32 samples were measured
†Median absolute deviation

The C_i plot displayed a water repellency characteristic at approximately 50 % of the individual sampling sites. This water-repellency was determined by visual inspection of the lack of water movement (or extremely slow infiltration rates) from the permeameter into the soil following the wetting of the contact sand. The water-repellent nature of the soil required leaving the disk permeameter on the soil for a longer period of time to allow for the infiltration rate to reach steady state.

Following the skewness test, it was determined that the K_s data from the two control plots was not 'normal' (i.e. the skewness values did not fall within the critical skewness range) and therefore required the use of the nonparametric Mann-Whitney U test. A significant difference existed for the saturated hydraulic conductivity between the two control plots, with a p-value of <0.01 (Table 4).

Table 4
Statistical differences at plots C_i and C_a

C_i vs C_a	p-value*	Statistical Test
K_s	**< 0.01**	Mann-Whitney U test
S	**< 0.01**	Mann-Whitney U test
$\rho_{b\ top\ 45}$	**< 0.01**	Mann-Whitney U test
$\rho_{b\ bottom\ 45}$	**< 0.01**	Mann-Whitney U test
$\rho_{b\ 90}$	**< 0.01**	Unpaired means test
LOI	**< 0.01**	Mann-Whitney U test

***Bold** indicates significant difference

The box plot (Figure 7) displays this significant difference well. The box plot indicates no overlap in the 95 % confidence bands about the median, and therefore is a robust visual tool of the difference between the two plots. Thus, C_a has a significantly higher infiltration rate than C_i. Due to this difference in the control plots, it was determined that forested plots of one soil type must be directly compared with the appropriate control to infer the effects of forest species on K_s.

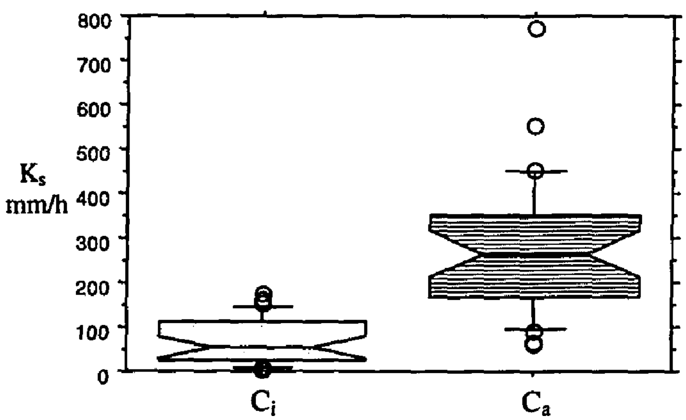

Figure 7. Notched Box Plots: K_s values for both control plots.

3.1.2 *Influential Factors*

Bulk Density (ρ_b)

The bulk densities (ρ_b) of the two control plots were also investigated, both for the top 5 cm (90 cm^3 core) and the top 2.5 cm (top 45 cm^3 core) of the soil surface layer. C_i had lower mean values for both $\rho_{b\,90}$ and for $\rho_{b\,top\,45}$ than C_a (Table 3).

The values for both $\rho_{b\,90}$ and $\rho_{b\,top\,45}$ were significantly different between the two control plots (Table 4; Figure 8). The skewness test indicated that the $\rho_{b\,90}$ values were 'normal', and therefore the parametric unpaired means test was used to compare both control $\rho_{b\,90}$. There was a significant difference with a p-value of <0.01.Similarly, the Mann-Whitney U test was used to compare the two control $\rho_{b\,top\,45}$ and determined there was also a strong significant difference with a p-value of <0.01 (Table 4; Figure 9).

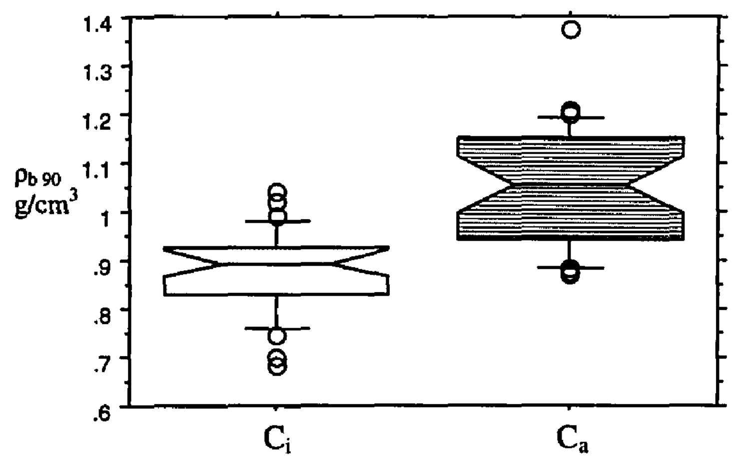

Figure 8. Notched Box Plots: Bulk Density (90 cm^3 core) samples from both control plots

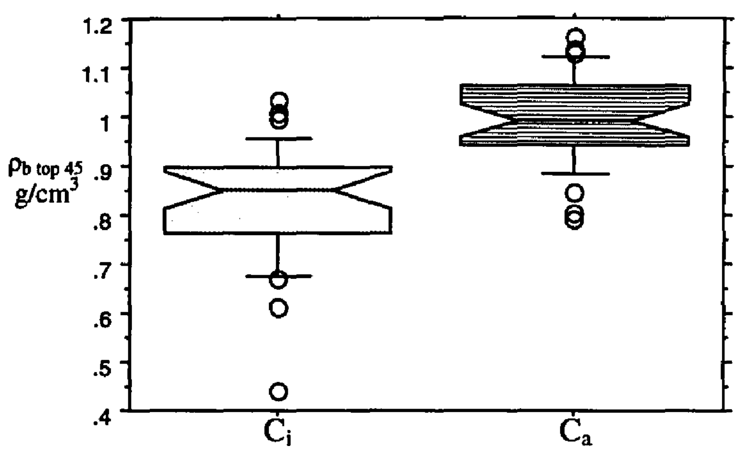

Figure 9. Notched Box Plots: Bulk Density (top 45 cm^3 core) samples from both control plots

To examine whether the bulk density was correlated with K_s in the two control plots, the Spearman rank correlation test, a non-parametric test, was utilized. No significant correlation was determined for either C_i or C_a in reference to K_s and $\rho_{b\,90}$, with correlation coefficients (r_s-value) of -0.121 ($p = 0.50$) and 0.113 ($p = 0.55$), respectively (Table 5). In addition, no correlation was determined for either C_i or C_a in reference to the K_s and the $\rho_{b\ top\ 45}$ values, with an r_s-value of -0.082 (p = 0.65) and 0.205 (p = 0.28), respectively. Therefore, no matter what the depth the core is taken for the bulk density measurement, no significant correlation exists between K_s and bulk density.

I also investigated whether a correlation existed between $\rho_{b\ 90}$ and $\rho_{b\ top\ 45}$ for both control plots. According to Wood (1977), Hawai'i inceptisols typically have bulk densities that decrease with depth. A strong positive correlation did exist at both C_i and C_a, with r_s-values of 0.684 (p = <0.01) and 0.663 (p = <0.01), respectively (Table 5). Therefore, as the soil density increased in the top 2.5 cm, the density also increased in the 2.5-5 cm range.

Table 5
Spearman correlations at plots C_i and C_a

Correlations	C_i r_s-value	C_i (p-value)*	C_a r_s-value	C_a (p-value)
K_s and $\rho_{b\ top\ 45}$	-0.082	(0.65)	0.205	(0.28)
K_s and $\rho_{b\ 90}$	-0.121	(0.50)	0.113	(0.55)
K_s and LOI	**-0.425**	**(0.02)**	-0.157	(0.41)
$\rho_{b\ top\ 45}$ and $\rho_{b\ bottom\ 45}$	**0.684**	**(<0.01)**	**0.663**	**(<0.01)**
$\rho_{b\ top\ 45}$ and LOI	**-0.452**	**(0.01)**	-0.290	(0.11)

*__Bold__ indicates significant correlation

Organic Matter Content (LOI)

Loss-on-ignition (LOI) was used to estimate the organic matter content of the specific soil types under different vegetation types, and thus was also being examined within the control plots as well. LOI values of the control plots were compared using the Mann-Whitney U test and found to be statistically significant with a p-value of <0.01 (Table 4; Figure 10). The mean LOI values for C_i were significantly higher than those of C_a with values of 18.7% and 16.0%, respectively (Table 3).

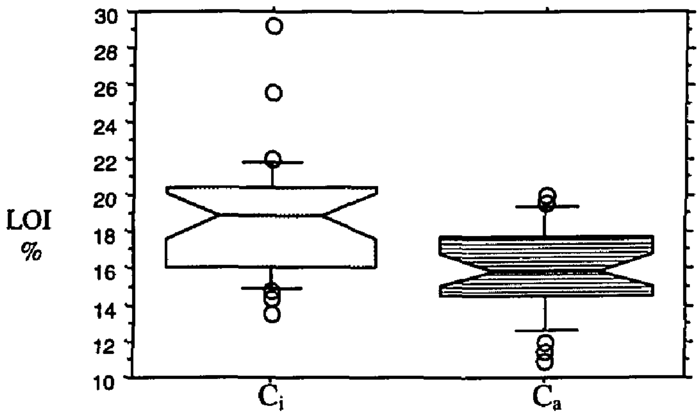

Figure 10. Notched Box Plots: LOI for both control plots.

A relationship between K_s and LOI was also explored using the Spearman rank correlation test. At the C_i plot a strong and significant negative correlation did exist with an r_s-value of -0.425 ($p = 0.02$) (Table 5). However, in the C_a plot, there was no correlation with an r_s-value of -0.157 ($p = 0.41$). Therefore, according to this data set, as the organic matter content of the soil in C_i increased the K_s value decreased, contrary to expectations.

In addition, I examined whether a correlation existed between LOI and $\rho_{b\ top\ 45}$ for both control plots. There was a negative correlation for the C_i plot, with an r_s-value of -0.452 ($p = 0.01$), indicating that as organic matter content increased the bulk density decreased, as expected. However, in the C_a plot, with an r_s-value of -0.290 ($p = 0.11$), no correlation was present and thus the amount of organic matter in the soil at C_a does not correlate with bulk density.

3.2 Forest Plantations

Analysis of the K_s data in the control plots indicated that a significant difference exists between the two controls. Therefore, further analysis of the study plots required a separation of the areas based on soil type. Forest plantations of one soil type are compared with the appropriate control and forest species of the same soil type. In addition, the physical and chemical soil characteristics, considered important in characterizing the hydrologic properties of the soil, are again analyzed for their significant differences and correlations.

3.2.1 Saturated Hydraulic Conductivity (K_s)

The four forested stands, *A. confusa* (A_a), *E. robusta* (E_a and E_i), and *F. uhdei* (F_i), as well as the two control plots (C_i and C_a) were examined and the K_s and sorptivity (S) values determined (Table 6).

Within the inceptisol soil, the K_s values for C_i and E_i were considerably lower than for the F_i area, and both C_i and E_i appeared to have water-repellent soils (Figure 11).

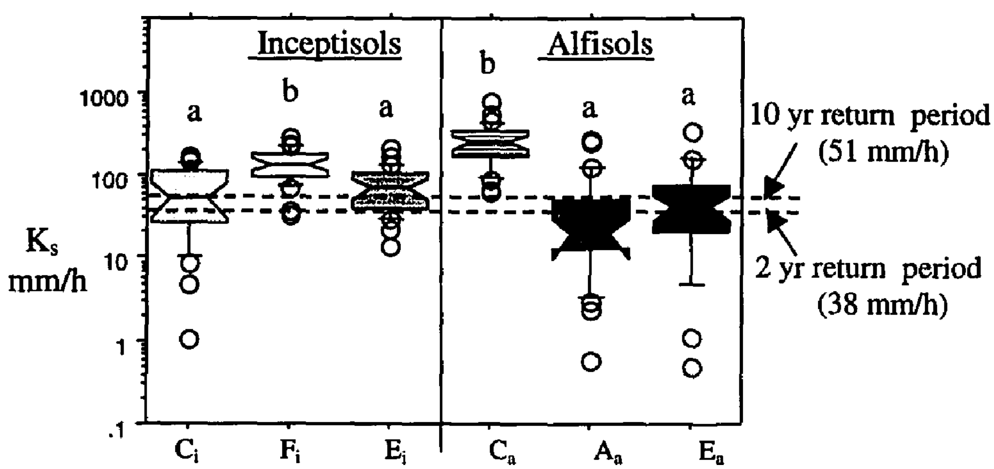

Figure 11. Notched Box Plots: K_s values (Log-scale) for all six study plots. For a given soil, study plots with the same letter are not significantly different at $\alpha = 0.05$.

Table 6
Descriptive statistics of hydrological, physical, and chemical soil characteristics for all study plots.

Control areas	C_i	F_i	E_i	C_a	A_a	E_a
n	32	35 (38*) (36†)	26 (32‡)	29 (32‡)	31 (32‡)	35 (36‡)
K_s (mm/h)						
Mean	71.6	142.7	78.1	276.8	48.9	67.5
Std. Dev.	51.8	60.0	49.3	156.6	67.2	80.9
Median	53.9	138.3	70.0	263.2	19.9	41.9
MAD	39.3	39.3	32.4	91.1	15.4	30.2
Minimum	1.1	32.6	13.4	64.0	0.6	0.5
Maximum	174.1	292.6	223.4	776.3	268.8	337.8
$\rho_{b\,90}$ (g/cm^3)						
Mean	0.876	0.952	0.816	1.052	1.068	0.701
Std. Dev.	0.085	0.153	0.145	0.124	0.127	0.110
Median	0.893	0.958	0.794	1.054	1.033	0.690
MAD	0.050	0.093	0.123	0.104	0.069	0.055
Minimum	0.685	0.566	0.561	0.871	0.830	0.519
Maximum	1.040	1.199	1.109	1.373	1.397	0.947
$\rho_{b\,top\,45}$ (g/cm^3)						
Mean	0.824	0.875	0.690	0.993	1.018	0.598
Std. Dev.	0.119	0.182	0.151	0.091	0.136	0.139
Median	0.851	0.898	0.716	0.991	0.982	0.629
MAD	0.056	0.103	0.119	0.054	0.057	0.057
Minimum	0.441	0.288	0.420	0.791	0.813	0.255
Maximum	1.034	1.250	0.924	1.164	1.429	0.792
LOI (%)						
Mean	18.7	23.2	29.8	16.0	19.8	33.0
Std. Dev.	3.3	6.2	9.1	2.4	4.2	7.1
Median	18.9	22.5	26.2	15.9	19.9	31.3
MAD	1.7	4.1	5.3	1.7	3.3	2.4
Minimum	13.5	14.3	18.3	11.0	12.0	23.7
Maximum	29.2		42.0	49.5	20.0	27.1
	54.9					

*Number of bulk density samples measured
†Number of LOI samples measured
‡ Number of bulk density and LOI samples measured

Roughly 50 % and 35-40 % of the sampling sites within C_i and E_i, respectively, would repel water for over 1 h at times, dramatically affecting final K_s values. To investigate significant differences between these plots, the K_s data were analyzed using the Kruskal-Wallis (three or more sample) non-parametric test followed by pair-wise Mann-Whitney U tests. The results indicated that the C_i vs F_i and the F_i vs E_i areas were significantly different with p-values of <0.01 (Table 7). However, there was no significant difference between C_i and E_i with a p-value of 0.51. The results indicate the similarity in the water-repellent characteristics of both C_i and E_i plots.

Table 7
Statistical differences for all six study plots

Areas	K_s	$\rho_{b\ top\ 45}$	$\rho_{b\ 90}$	LOI	Statistical tests*
C_i vs F_i	**<0.01**	0.07	**0.02**	**<0.01**	a, b, c, d
C_i vs E_i	0.51	**<0.01**	0.07	**<0.01**	a, b, c, d
F_i vs E_i	**<0.01**	**<0.01**	**<0.01**	**<0.01**	a, b, c, d
C_a vs A_a	**<0.01**	0.95	0.64	**<0.01**	a, a, d, a
C_a vs E_a	**<0.01**	**<0.01**	**<0.01**	**<0.01**	a, a, d, a
A_a vs E_a	0.12	**<0.01**	**<0.01**	**<0.01**	a, a, d, a

Bold indicates significant difference
*a - Kruskal-Wallis followed by Mann Whitney at $\alpha = 0.05/3$ or $\alpha = 0.017$ (R. Sutherland, University Hawai'i Dept. Geography, pers. comm., 2003); b - ANOVA and Fisher's PLSD *(squared transformation)*; c – ANOVA and Fisher's PLSD; d - ANOVA and Fisher's PLSD test (log transformation)

Within the alfisol soil, both of the forest stands had much lower infiltration rates than the corresponding control plot, with mean K_s values of 49 and 68 mm/h for A_a and E_a, respectively, and 277 mm/h for C_a (Table 6). Both the A_a and E_a plots revealed a water-repellent characteristic, similar to that of C_i and E_i creating extremely slow infiltration rates into the soil surface. Approximately 75 and 45 % of the sampling sites within plots A_a and E_a, respectively, displayed this water-repellent characteristic.

Again, the Kruskal-Wallis test was used to protect the data set and was followed by the Mann-Whitney U test, a non-parametric test, to determine that there was a significant difference between the K_s of the forested plots and the control plot with p-values of <0.01 for both (Table 7). However, there was no difference between the two forest plots, A_a and E_a, with a p-value of 0.12.

3.2.2 Influential Factors

Bulk Density (ρ_b)

The bulk densities from the 90 cm^3 core and top 45 cm^3 core samples indicated the inceptisol plots had relatively similar values (Table 6). ANOVA, followed by Fisher's PLSD post-hoc test, was used to examine $\rho_{b\ 90}$. ANOVA was also used to examine $\rho_{b\ top\ 45}$, however, this data set required a squared transformation for normality. The results indicate that there was a significant difference among almost all of the values, with the exception of C_i vs E_i for $\rho_{b\ 90}$ with a p-value 0.07 and for C_i vs F_i for $\rho_{b\ top\ 45}$ with a p-value 0.07 (Table 7). A box plot illustrates these differences well (Figures 12 & 13).

Similar to the bulk densities in the inceptisol soil type, the *E. robusta* in the alfisol soil type had the lowest bulk density within the samples, for both $\rho_{b\ 90}$ and for $\rho_{b\ top\ 45}$ (Table 6). To examine the difference among the $\rho_{b\ 90}$ data set, it was necessary to use log transformations for normality, and then apply ANOVA followed by Fisher's PLSD post-hoc test (Table 7). The results indicated that there was a significant difference between C_a and E_a and between A_a and E_a with p-values of <0.01. However, there was no difference between C_a and A_a with a p-value of 0.64. The box plot in Figure 12 illustrates well the significant difference in the bulk density in top 5 cm of soil between the E_a plot and C_a and A_a.

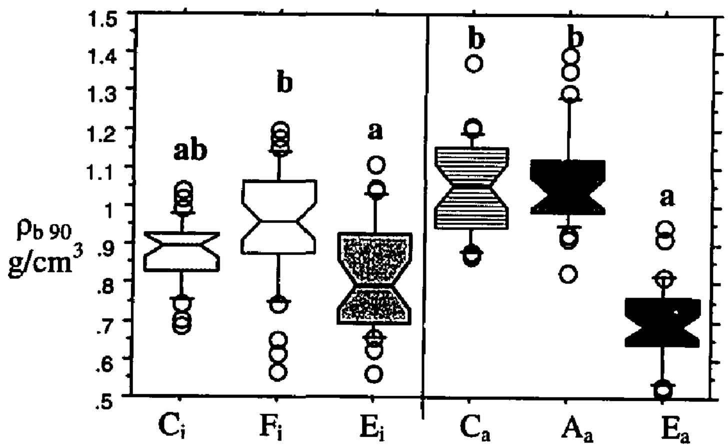

Figure 12. Notched Box Plots: Bulk density values from 90 cm^3 cores for all six study plots. For a given soil, study plots with the same letter are not significantly different at $\alpha = 0.05$.

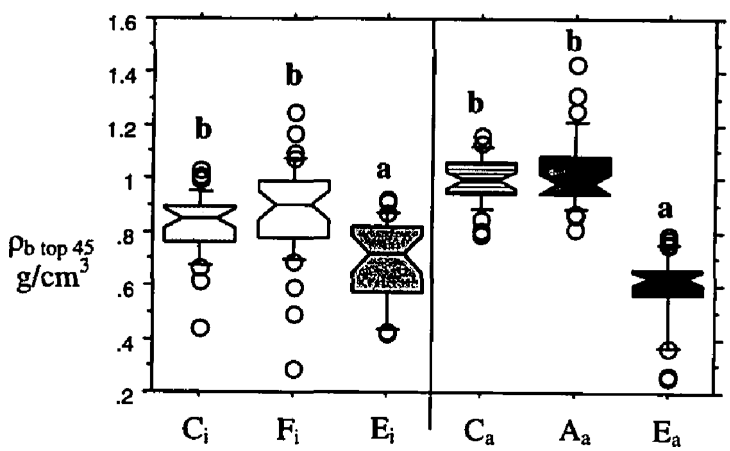

Figure 13. Notched Box Plots: Bulk density values from top 45 cm^3 cores for all six study plots. For a given soil, study plots with the same letter are not significantly different at $\alpha = 0.05$.

Differences were also examined for the $\rho_{b\ top\ 45}$ data set, applying the Kruskal-Wallis test followed by the Mann-Whitney U test (Figure 13). The results were similar to that of the above $\rho_{b\,90}$ data, indicating a significant difference between C_a and E_a and between A_a and E_a with p-values of <0.01. However, there was no difference between C_a and A_a with a p-value of 0.95.

To examine the effects of bulk density on K_s, the Spearman rank correlation test was applied. No significant correlation resulted at $\alpha = 0.05$ for any of the plots within the inceptisol soil type, for either K_s vs $\rho_{b\,90}$ or K_s vs $\rho_{b\,top\,45}$ (Table 8). A correlation was also examined between $\rho_{b\,90}$ and $\rho_{b\,top\,45}$ for each inceptisol plot, to examine how the bulk density changed in the vertical profile of the soil surface. A significant positive correlation resulted at α level 0.05 for the forest and control sites. Therefore, the density of the soil increased with depth, an unexpected result according to Wood (1977).

Table 8
Spearman correlations for all six study plots

Plots	K_s and $\rho_{b\,top\,45}$	K_s and $\rho_{b\,90}$	K_s and LOI	$\rho_{b\,top\,45}$ and $\rho_{b\,bottom\,45}$	$\rho_{b\,top\,45}$ and LOI
			r_s-value (p-value)*		
C_i	-0.082 (0.65)	-0.121 (0.50)	**-0.425 (0.02)**	**0.684(<0.01)**	**-0.452 (0.01)**
F_i	0.148 (0.39)	0.106 (0.53)	-0.165 (0.34)	**0.786(<0.01)**	**-0.888(<0.01)**
E_i	0.288 (0.15)	0.30 (0.13)	-0.361 (0.07)	**0.909(<0.01)**	**-0.930(<0.01)**
C_a	0.205 (0.28)	0.113 (0.55)	-0.157 (0.41)	**0.663(<0.01)**	-0.290 (0.11)
A_a	-0.089 (0.63)	-0.252 (0.17)	0.049 (0.79)	**0.673(<0.01)**	**-0.698(<0.01)**
E_a	-0.062 (0.72)	-0.033 (0.85)	0.026 (0.88)	**0.645(<0.01)**	**-0.823(<0.01)**

*__Bold__ indicates significant difference

Similar correlations using the Spearman rank correlation test were made for the plots in the alfisol soil type. Results indicated no significant correlation for either K_s vs $\rho_{b\,90}$ or K_s vs $\rho_{b\,top\,45}$ (Table 8). The Spearman rank correlation test was also applied to examine the relationship between the bulk densities from the top 2.5 cm and top 5 cm of soil. There were significantly positive correlations for all of the plots in the alfisol soil type at $\alpha = 0.05$.

Organic Matter Content (LOI)

Organic matter content, using LOI, was estimated for all study plots. Both E_i and E_a resulted in the highest mean organic matter content of 30 and 33%, respectively (Table 6). The control plots (C_i and C_a) had the lowest mean LOI values of 19 and 16%, respectively.

To evaluate differences in LOI among the inceptisol plots, ANOVA and Fisher's PLSD post-hoc test, following log transformation, were utilized (Table 7). All plots in the inceptisol soil type were considered significantly different as illustrated in Figure 14.

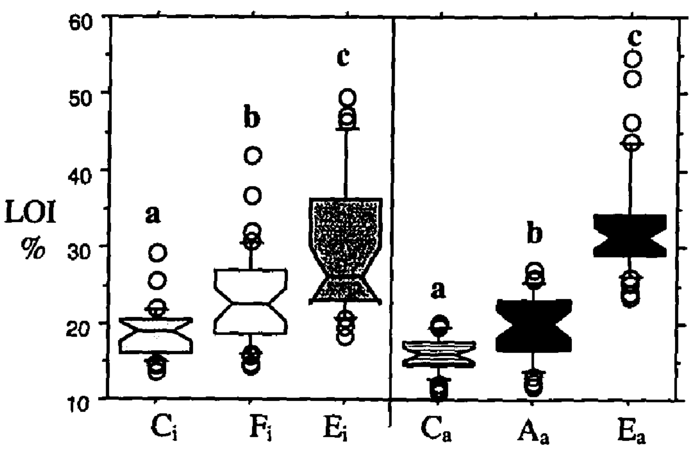

Figure 14. Notched Box Plots: LOI values for all six study plots. For a given soil, study plots with the same letter are not significantly different at $\alpha = 0.05$.

To evaluate differences in LOI among the alfisol plots, Kruskal-Wallis was used to protect the data set, followed by the Mann-Whitney U test. Similar to the strong significant differences in the inceptisol soil plots, all of the alfisol soil plots were significantly different from each other at $\alpha = 0.05$.

The Spearman rank correlation test was applied to investigate the relationship between K_s and LOI for both the inceptisol and alfisol soil plots. Results for the inceptisol plots indicated that only at the control plot was there a significant correlation with an r_s-value of –0.425 ($p = 0.02$) (Table 8). The results from C_i were unexpected, with a negative correlation indicating that when the organic matter content increased, K_s decreased. Within the alfisol plots, results indicated no significant correlations at $\alpha = 0.05$.

The Spearman rank correlation test was also used to examine the relationship between LOI and $\rho_{b\ top\ 45}$ for both soil types. All plots within the inceptisol soil type resulted in significant negative correlations as expected. Therefore, as the organic matter increased the bulk density in the upper 2.5 cm decreased. This was also the case for both forest plots in the alfisol soil, with A_a and E_a displaying significant negative correlations with r_s-values of -0.698 and -0.823, respectively, and p-values of <0.01. However, at the control plot, LOI and $\rho_{b\ top\ 45}$ were not significantly correlated, with an r_s-value of -0.290 ($p = 0.11$).

3.3 Discussion

Initial inspection of the results indicates that the two control plots were significantly different from each another in all measured soil attributes. Therefore, all subsequent analyses required forested plots in one soil type to be compared only with the control from the same soil type. Although the control plots contained the same grass species (*T. insularis*) and roughly the same site characteristics, aside from the different soil types, the control in the inceptisol (C_i) had one obvious characteristic that was completely different – the soil was water-repellent.

This water-repellent soil property was observed in the field when the water volume in the disc permeameters moved extremely slowly once the contact sand was wetted, for upwards of 1 h in some sites. The water-repellency had a high spatial variability throughout the C_i plot, with roughly 50 % of the sampling sites exhibiting this characteristic minimally or not at all, a condition common in water-repellent soils (Dekker and Ritsema, 1996; Dekker and Ritsema, 2000) (Figure 13). This was also revealed in the significantly lower K_s values of C_i with a median value of 54 mm/h compared to that of the control in the alfisol soil (C_a) with a median value of 263 mm/h. Even with the abundance of ant holes discovered in the C_i site, the infiltration rates were lower, an unexpected result considering the findings by Williams and Bonell (1988). They consider these types of activities, such as holes from termites and ants, as significant in producing macropores for water flow that would usually be associated with high values of K_s.

Additional field measurements for K_s in the specific forest species also revealed this water-repellent property in both the alfisol and inceptisol soil types. The soils in the *A. confusa* (A_a), and both *E. robusta* (E_a and E_i) plots all displayed some level of water-repellency, and again the data was highly variable. Approximately 75 % of the A_a samples, 45 % of E_a samples, and 35-40 % of E_i samples displayed this water-repellency (Figure 13). It was not surprising then that all four plots (including the C_i site) contained the lowest median K_s values, between 20 and 70 mm/h, a rather narrow range of values for four separate plots in two soil types. This differed significantly from the infiltration rates of the two plots that did not display a water-repellent characteristic, namely F_i and C_a, with rates of 138-263 mm/h. Thus, it seems apparent that the water-repellency caused the lower infiltration rates in these sites. But what processes created the water-repellency?

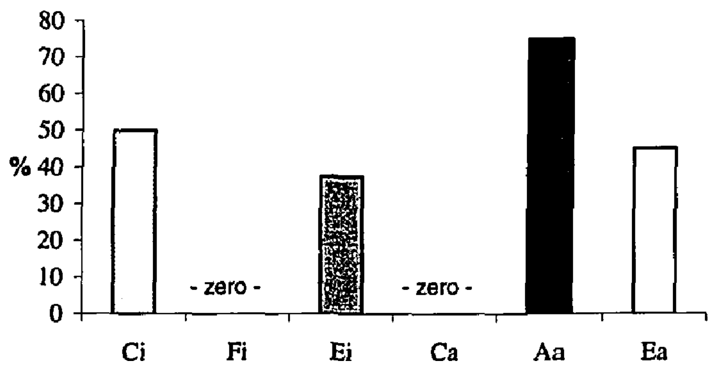

Figure 15. Percentage of sampling sites within study plots that display a water-repellent characteristic.

For the forested soil plots, the answer may lie in the vegetation itself. The two species, *E. robusta* (E_a and E_i) and *A. confusa* (A_a), are both considered allelopathic species, *F. uhdei* (F_i) is not. Soil water-repellency is considered a function of the type of organic matter incorporated in the soil matrix, or the precipitation of organic substances in the soil. A few mechanisms have been suggested to cause this condition, such as organic substances from the plant litter, microbial by-products like fungal mycelia, and fires (Doerr et al., 1996; Dekker et al., 2000). The allelopathic species studied here appear to correlate well with water-repellent soil conditions. It seems reasonable that the vegetation and vegetative litter, likely from the waxy coating on the leaves of *Eucalyptus* and *Acacia* create both allelopathy and water-repellent soil surfaces. Franco et al. (2000) found components of hydrophobic polar wax extracts from the leaves and litter of plants, found components of hydrophobic polar wax extracts from the leaves and litter of plants, similar to those found in *Eucalyptus* spp., on the surface of water-repellent soils. But this does not explain the control plot (C_i) that also displayed a water-repellent property to the soil and did not contain vegetation with a known allelopathic nature. Thus, some other mechanism must be involved to explain the K_s behavior in C_i.

Control plot (C_i) is a more recent site for agricultural practices and controlled burns than the forests examined. Although no official records were located of fire occurrence at this specific site, this practice is considered commonplace in this agricultural landscape of central O'ahu. In the pineapple fields, the fields are burned roughly every 4-5 years while also burning the plastic used to cover the soil (T. Giambelluca, Univ. Hawai'i, Dept. Geography, pers. comm., 2003). Research into the correlation of fires and soil hydrophobicity has been on-going for decades, and conclusive evidence is still lacking (Hussain et al., 1969; Doerr et al., 1996 & 1998). However, the burning of plastic and its effects on soil hydrophobicity have not been studied extensively. There are few other explanations that can be clearly drawn regarding the water-repellency of this plot. But why is there not a similar situation occurring at the other control plot (C_a)? With the plots approximately 5,000 m from one another, it is possible that the fires at C_a were not used as recently as they were at C_i, were not as frequent, or that fire had a different effect on the different soil types. In addition, hydrophobicity is spatially variable and may simply be more sporadic or less pronounced at C_a. This might help to explain the difference between the two control plots.

Referring back to Figure 9, the box plot indicates the range of K_s values at each study plot as well as intense rainfall episodes at both 2 and 10 yr return periods. The figure illustrates that all four of the plots containing water-repellent samples have values below both the 2 and 10 yr return periods for 1 h duration rainfalls of 38 and 51 mm/h, respectively, indicating that runoff at these rates can occur. The four plots with water-repellent characteristics are represented in Figure 14. The figure displays only the samples determined to be water-repellent and the number of samples that fall below the 2 and 10 yr return periods. Values below the 38 and 51 mm/h threshold represent sites where HOF can occur. Table 9 represents the percentage of water-repellent samples that fall below the 38 and 51 mm/h threshold as well as the percentage of non water-repellent samples that fall below these values.

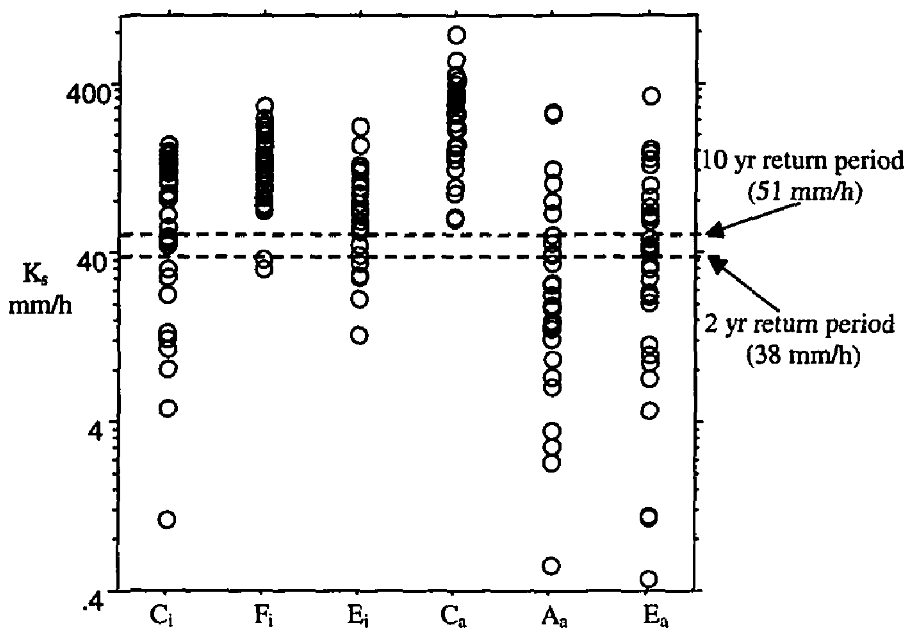

Figure 16. K_s (in log scale) from study plot samples in relation to intense rainfall episodes at both 2 and 10 yr return periods

Previous studies (Waterloo, 1994; Rawls et al., 1998; Burk, 1999) have indicated a strong negative correlation between K_s and bulk density. When the density of the soil increases, the infiltration rate decreases. Nakaya and Motomura (1984) explained that even when bulk density decreases and helps to improve water permeability and retention, the hydrophobicity can restrict these physical properties, and thus this water-repellency becomes a crucial factor when investigating soil properties. The results obtained in this research support Nakaya and Motomura's findings. No correlation, either positive or negative, could be found between the upper 2.5 cm bulk density and K_s or between the upper 5 cm bulk density and K_s at any of the six study plots (Table 10).

Table 9
Percentage of water-repellent and 'wettable' soil samples with K_s below both 2 and 10 yr return periods for 1 h duration intense rainfall episodes for all plots.

Plot n	< 51 mm/h (%)	< 38 mm/h (%)	< 51 mm/h (%)	< 38 mm/h (%)
	water-repellent soils		wettable soils	
C_i (15,17)*	93	67	12	0
F_i (0, 35)	0	0	0	6
E_i (9,17)	67	56	12	6
C_a (0, 29)	0	0	0	0
A_a (15,17)	96	82	25	13
E_a (23,8)	100	67	35	25

*First number in parentheses represents number of water repellent samples and second number in parentheses represents number of non water-repellent samples.

The findings in this study, especially the lack of correlation between K_s and bulk density, seem reasonable for the water-repellent plots, but what about for the other plots, F_i and C_a? F_i might be explained by the Foote et al. (1972) description of the mahana soil series which stated that: "The A horizon contains an accumulation of iron and titanium oxides, which appear as small, dark-colored, shiny specks, and therefore has a much higher bulk density than is usual for soils derived from volcanic ash". Thus, with mahana soils having higher bulk densities than is typical of other soils derived from volcanic ash, a significant correlation may be difficult to derive. As for the C_a plot, there is no definitive explanation. This plot contains the lowest mean percentage of organic matter of 16%, yet has the highest average infiltration rates of 277 mm/h.

Table 10
Spearman correlations of investigated soil attributes for individual study plots

Correlations	Alfisols			Inceptisols		
at $\alpha = 0.05$	C_a	A_a	E_a	C_i	F_i	E_i
K_s and $\rho_{b\ top\ 45}$	O	O	O	O	O	O
K_s and $\rho_{b\ 90}$	O	O	O	O	O	O
K_s and LOI	O	O	O	-	O	O
$\rho_{b\ top\ 45}$ and $\rho_{b\ bottom\ 45}$	+	+	+	+	+	+
$\rho_{b\ top\ 45}$ and LOI	O	-	-	-	-	-
Significant Characteristics						
Water-repellent soil	O	X	X	X	O	X
Allelopathy	O	X	X	O	O	X

'-' = negative correlation exists
'+' = positive correlation exists
X = exhibits this characteristic
O = no correlation exists or does not exhibit this characteristic

Correlations were also investigated between K_s and LOI for the six plots, resulting in only one negative correlation for C_i. It seems reasonable that there would not be a correlation between these two attributes, because it is the organic matter that is likely creating the hydrophobic nature of the soil, and therefore an increase in organic matter might decrease the infiltration rate rather than increasing it as expected. However, for the water-repellent sites, a negative correlation might also be considered a reasonable result, as is the case with site C_i. The reasoning follows that if the organic matter in the soil assists in creating this water-repellency, then the less organic matter that is present the higher the infiltration rates will be. This correlation or lack of one between K_s and LOI can be summed up again by a statement from Nakaya and Motomura (1984) that although soil organic matter increases porosity and thus infiltration, it also creates hydrophobicity, with the net effect a function of these two contradictory factors. In this study, either no significant correlation or a negative correlation for the water-repellent plots would thus be expected.

Additional results indicated a negative correlation between the bulk density from the top 2.5 cm of the soil and the organic matter content, indicating that when the organic matter is high, the bulk density is typically lower. This finding is similar to other such findings, however, in this study this was the case for all plots with the exception of plot C_a. The C_a plot had the lowest mean LOI at 16%, significantly lower than that of plot C_i with the next lowest mean LOI value of 19%. There are a high number of small roots in the soil surface of the grass, yet the small roots likely make up a small percentage of the organic matter content. This would thus yield a strong negative correlation for both control plots. However, plot C_a did not indicate this result, although it was not far off with an r_s-value of -0.29 ($p = 0.11$). Table 11 below indicates some of the significant differences investigated in this study.

Table 11
Differences of investigated soil attributes between individual study plots

Differences at $\alpha = 0.05$	K_s	$\rho_{b\ top\ 45}$	$\rho_{b\ 90}$	LOI
C_a vs C_i	H	H	H	L
C_a vs A_a	H	O	O	L
C_a vs E_a	H	H	H	L
A_a vs E_a	O	H	H	L
C_i vs F_i	L	O	L	L
C_i vs E_i	O	H	O	L
F_i vs E_i	H	H	L	L

H = value of first plot is significantly higher than second plot
L = value of first plot is significantly lower than second plot
O = indicates no significant difference

Referring back to studies conducted by Wood (1971; 1977), he found water-repellency in the soil under an *E. globulus* forest type. Although he sampled other forested sites that included *E. robusta* and *A. confusa*, he did not find water-repellency at any other site. Wood's sample size was relatively small with three samples under each different land cover. With the high variability in both infiltration rates and water-repellent soils, the water-repellent characteristic may not have been revealed for the specific reason of small sample size.

In closing, it is interesting to refer back to Schuyler and Allardt's (1889) statement, given earlier, regarding surface runoff on degraded slopes when rainfall exceeds 1 – 2" in a 24 h period, or roughly 25 – 51 mm/24 h. As discussed previously, the Honouliuli Preserve in the late 1800's still lacked forest cover during this time since major planting efforts had not taken effect till years later. Although their statement can be considered a qualitative observation, it is interesting to note that they witnessed HOF at this time. The control plots of today are likely not that representative of soil conditions prior to re-planting, with the overgrazing that was occurring at that time contributing to higher soil compaction. The infiltration rates today are likely higher due to decreased bulk densities, on the other hand, the addition of forest species that create a water-repellent soil surface have decreased the infiltration rates of the region. The net result is that forest plantations are an improvement to soil hydrological properties in comparison to the denuded landscape prior to planting. Because there are no native vegetation control sites to compare against, it is difficult to assess whether the plantations are an improvement to the soil hydrological properties of native vegetation. It is reasonable to assume, however, that the native vegetation, with it's layers of understory and thick litter layer, is more beneficial to the soil hydrological properties than the monotypic forest plantations are.

Chapter 4. Conclusion

Prior to the massive planting effort that took place over 70 years ago, high runoff and erosion was recorded on the slopes of the Wai'anae Mountains due to the destruction of the native vegetation. Has runoff and erosion been minimized now that the region is covered with non-native, monotypic forest plantations?

Instead of 5,000 head of cattle grazing the slopes of the Honouliuli Preserve in the Wai'anae Mountains, there are now only the occasional pigs digging up the soil. Although the detrimental effects of pigs on the landscape in Hawai'i are clear, it likely has not created the same magnitude of destruction that the combination of over-grazing, fires, and exposed soil had caused previously.

Of the six study plots examined, water-repellency was detected in four, with frequencies of 50 % (C_i), 35 % (E_i), 75 % (A_a), and 35-40 % (E_a), which resulted in lower infiltration rates with median K_s values of 15-39 mm/h compared to non water-repellent soils in C_a and F_i with values of 138 – 263 mm/h. Study plots that displayed this water-repellent characteristic had between 35-40 % (E_i) and 75 % (A_a) of the samples that were hydrophobic. Of the water-repellent samples, 56-82 % of these had K_s values of less than 38 mm/h, the threshold for 1 h duration rainfalls with a 2 yr return period.

The water-repellency was likely due to allelopathic vegetation in the forest plantations and periodic fires in the control site. Because of the combination of spatially variable water-repellency and similar variability in infiltration rates, significant correlations were difficult to assess. K_s and LOI were not significantly correlated, probably because the vegetative litter is creating hydrophobicity. In addition, no significant correlations were found between K_s and bulk density, probably because of the variable water-repellency.

This study has offered insight into the apparent water-repellent occurrence and variability of certain soil types under specific vegetative cover. The combination of minimal understory and low infiltration rates, associated with allelopathic and water-repellent conditions could increase HOF frequency and increase potential erosion (Ritsema and Dekker, 2000). There is current evidence of gullying in regions of the Preserve where allelopathic forest stands are located and HOF still occurs in this region.

Currently, we are looking at a 'snapshot' of the forest plantations rather than a typical steady-state forest ecosystem, with many of the plantations at roughly the same point in their life cycle. Smith (1985) makes an interesting point by stating that the natural process of aging or disease in a forest stand can create a population crash, and although common elsewhere among monotypic forests, they have yet to be recorded in non-native forest plantations in Hawai'i. Sanchez et al. (1985) indicate that when a tree reaches its last stages of growth or nears the end of its life cycle, the activity of the tree diminishes producing less litter and less of a protective canopy. Although this may not appear to be a problem with the forests plantations yet, time will come when there is a dieback due to age and/or disease. With a lack of vegetative understory and a water-repellent soil surface exposed to the direct impact of rainfall, this may lead to increased surface runoff and soil erosion. With so many regions in the tropics planted with monotypic *Eucalyptus* forests, there could be considerable implications for managing these regions.

From a management perspective within the Honouliuli Preserve, it may seem reasonable to focus attention on forest sites that contain mainly allelopathic species. These sites may be contributing to the bulk of HOF in the Preserve and increasing the potential for soil erosion.

4.1 *Suggestions for Further Studies*

White et al. (1992) discussed some of the problems associated with the use of disk permeameters, including the assumptions that soil properties are uniform with depth and that the instrument is placed on level soil. Joel and Messing (2000) discovered problems using the permeameter on sloping lands due to the difficulty in applying a constant and even pressure to both the up-slope and down-slope sides of the disc. However, they did conclude that the permeameter was still the best instrument available at the time for determining infiltration rates.

Follow-up studies on the extent of this water-repellent soil property in Hawai'i would benefit our understanding of the causes and effects of this characteristic. If the vegetative litter is removed, does the soil hydrophobicity decrease or become non-existent and at what rate? Is the vegetation or vegetative litter creating this condition and is it correlated to only allelopathic plants? Does a combination of fires and specific soils and/or vegetation create these conditions? There is a great deal more to learn from the interactions of the soil, vegetation, and hydrology in the Honouliuli Preserve.

Appendix A. All K_s values and associated S, θ_n, and θ_0

Control in Inceptisol (C_i)

Measurement No.	K_s* (mm/h)	S† ($m/s^{1/2}$)	θ_n‡	θ_0□
1	48.8	6.46E-06	0.33	0.40
2	23.2	2.16E-05	0.27	0.33
3	133.9	1.59E-06	0.26	0.36
4	12.6	4.93E-04	0.17	0.19
5	103.7	1.36E-04	0.23	0.25
6	144.2	1.83E-04	0.27	0.36
7	4.8	4.16E-05	0.30	0.55
8	47.2	3.46E-05	0.31	0.52
9	10.9	8.63E-04	0.19	0.43
10	67.3	2.20E-04	0.29	0.53
11	1.1	6.58E-06	0.25	0.42
12	153.2	2.95E-04	0.23	0.26
13	47.3	9.77E-05	0.34	0.43
14	85.5	1.23E-04	0.33	0.56
15	22.6	4.92E-06	0.19	0.35
16	8.4	1.97E-04	0.22	0.33
17	32.5	6.20E-05	0.20	0.29
18	123.4	1.89E-04	0.12	0.32
19	50.6	2.27E-06	0.15	0.32
20	163.9	4.50E-05	0.11	0.20
21	106.8	1.77E-05	0.23	0.33
22	45.2	6.20E-05	0.24	0.28
23	29.5	4.37E-05	0.29	0.32
24	57.2	1.53E-05	0.20	0.32
25	139.0	1.58E-04	0.27	0.32
26	174.1	1.34E-04	0.30	0.35
27	50.2	1.77E-05	0.25	0.36
28	92.4	5.12E-04	0.23	0.44
29	91.1	2.45E-05	0.24	0.31
30	13.7	1.58E-05	0.25	0.35
31	88.2	4.80E-04	0.23	0.36
32	118.7	7.35E-05	0.21	0.38

*Saturated hydraulic conductivity
†Sorptivity
‡Initial gravimetric soil moisture content
□Ending gravimetric soil moisture content

***Fraxinus uhdei* in Inceptisol (F_i)**

Measurement No.	K_s (mm/h)	S ($m/s^{1/2}$)	θ_n	θ_0
1	128.5	2.93E-04	0.25	0.72
2	148.1	2.43E-04	0.26	0.28
3	37.8	1.77E-04	0.24	0.27
4	133.7	6.13E-04	0.27	0.44
5	72.0	6.39E-05	0.29	0.52
6	186.7	4.08E-04	0.27	0.45
7	101.6	8.79E-05	0.32	0.33
8	248.9	5.78E-04	0.33	0.46
9	212.2	2.32E-04	0.31	0.51
10	95.5	9.00E-05	0.28	0.64
11	153.3	4.63E-04	0.27	0.51
12	212.8	3.01E-04	0.25	0.37
13	177.4	7.69E-04	0.30	0.41
14	199.3	5.54E-04	0.29	0.44
15	76.8	1.33E-04	0.28	0.45
16	75.3	1.09E-04	0.23	0.32
17	117.9	2.26E-04	0.24	0.55
18	172.6	3.83E-04	0.27	0.56
19	138.3	2.79E-04	0.30	0.34
20	177.6	4.21E-04	0.35	0.53
21	233.5	2.65E-04	0.33	0.48
22	292.6	1.77E-04	0.34	0.51
23	96.7	4.17E-05	0.25	0.31
24	113.8	9.55E-05	0.27	0.33
25	132.4	2.91E-04	0.26	0.35
26	150.2	2.15E-04	0.22	0.27
27	74.4	4.05E-05	0.18	0.38
28	170.7	1.34E-04	0.23	0.42
29	86.7	8.98E-05	0.23	0.30
30	32.6	9.87E-05	0.24	0.40
31	142.1	3.04E-04	0.19	0.22
32	110.1	1.51E-04	0.23	0.32
33	153.0	6.96E-04	0.22	0.28
34	224.4	6.10E-04	0.17	0.25
35	116.1	1.16E-04	0.23	0.26

***Eucalyptus robusta* in Inceptisol (E_I)**

Measurement No.	K_s (mm/h)	S ($m/s^{1/2}$)	θ_n	θ_0
1	45.3	9.66E-04	0.28	0.35
2	69.0	1.30E-04	0.20	0.31
3	125.5	3.95E-04	0.26	0.38
4	223.4	4.58E-04	0.27	0.42
5	30.0	2.07E-04	0.15	0.18
6	21.7	8.95E-05	0.17	0.31
7	176.6	8.38E-04	0.26	0.34
8	29.6	3.67E-04	0.24	0.28
9	133.2	2.66E-04	0.28	0.32
10	108.2	6.39E-04	0.28	0.35
11	72.9	3.11E-04	0.13	0.29
12	54.2	1.82E-04	0.19	0.34
13	39.7	2.26E-05	0.22	0.42
14	35.2	6.90E-05	0.23	0.31
15	13.4	3.79E-04	0.30	0.32
16	71.0	8.08E-04	0.33	0.37
17	35.4	9.43E-05	0.21	0.27
18	98.2	1.97E-04	0.15	0.25
19	72.4	1.41E-04	0.12	0.25
20	54.1	5.36E-04	0.12	0.32
21	57.9	2.73E-04	0.18	0.78
22	91.2	1.49E-04	0.26	0.32
23	106.6	7.95E-05	0.29	0.32
24	79.4	1.93E-04	0.21	0.36
25	63.1	3.62E-04	0.23	0.33
26	123.9	2.39E-04	0.21	0.28

Control in Alfisol (C_a)

Measurement No.	K_s (mm/h)	S ($m/s^{1/2}$)	θ_n	θ_0
1	553.7	5.89E-04	0.33	0.56
2	261.0	2.57E-04	0.26	0.32
3	776.3	9.17E-04	0.34	0.48
4	343.9	6.86E-04	0.32	0.39
5	324.1	5.03E-04	0.36	0.53
6	454.1	3.26E-04	0.26	0.37
7	175.5	1.29E-04	0.29	0.41
8	172.1	1.12E-03	0.30	0.44
9	347.7	7.69E-04	0.35	0.46
10	301.4	1.15E-04	0.25	0.28
11	92.1	1.82E-04	0.27	0.30
12	220.5	2.26E-04	0.28	0.37
13	144.7	8.05E-05	0.29	0.34
14	66.7	1.30E-04	0.25	0.37
15	157.9	1.83E-04	0.23	0.29
16	355.7	4.73E-04	0.27	0.32
17	99.6	2.02E-04	0.29	0.35
18	235.1	3.78E-04	0.26	0.42
19	440.3	6.13E-04	0.28	0.35
20	267.0	4.07E-04	0.28	0.31
21	64.0	3.18E-04	0.27	0.33
22	272.1	3.05E-04	0.27	0.44
23	127.4	3.95E-04	0.32	0.39
24	392.5	3.66E-04	0.32	0.34
25	312.7	2.02E-04	0.28	0.34
26	263.2	6.35E-04	0.27	0.32
27	175.0	7.12E-04	0.30	0.34
28	415.5	1.98E-04	0.26	0.33
29	216.5	2.59E-04	0.23	0.36

Acacia confusa in Alfisol (A_a)

Measurement No.	K_s (mm/h)	S ($m/s^{1/2}$)	θ_n	θ_0
1	104.5	1.97E-04	0.14	0.24
2	40.5	8.80E-06	0.20	0.21
3	6.7	1.84E-05	0.16	0.23
4	51.2	8.93E-06	0.18	0.34
5	2.3	1.33E-05	0.21	0.24
6	15.8	5.60E-06	0.18	0.29
7	35.3	7.81E-05	0.20	0.21
8	27.2	1.02E-04	0.15	0.29
9	19.2	1.34E-05	0.17	0.17
10	0.6	8.05E-06	0.15	0.23
11	12.7	1.29E-07	0.19	0.23
12	2.9	9.51E-05	0.14	0.18
13	9.6	1.82E-07	0.24	0.31
14	46.9	5.92E-06	0.24	0.53
15	26.2	1.37E-06	0.24	0.27
16	16.3	4.97E-05	0.21	0.25
17	81.6	1.72E-05	0.22	0.27
18	15.4	7.70E-05	0.21	0.25
19	125.9	6.26E-04	0.24	0.31
20	69.9	7.02E-04	0.24	0.32
21	19.8	1.52E-06	0.22	0.36
22	19.9	2.78E-04	0.20	0.28
23	19.0	2.03E-05	0.23	0.38
24	23.2	1.34E-05	0.21	0.26
25	3.6	2.50E-06	0.20	0.27
26	39.7	9.26E-06	0.21	0.34
27	126.6	9.15E-05	0.19	0.29
28	262.2	1.69E-04	0.14	0.29
29	268.7	1.31E-05	0.21	0.33
30	14.5	9.21E-07	0.23	0.37
31	7.5	9.47E-05	0.21	0.28

***Eucalyptus robusta* in Alfisol (E_a)**

Measurement No.	K_s (mm/h)	S ($m/s^{1/2}$)	θ_n	θ_0
1	41.3	2.35E-04	0.17*	0.19
2	44.8	2.69E-04	0.21	0.61
3	32.6	3.09E-04	0.18	0.48
4	42.7	2.66E-05	0.18	0.64
5	22.2	3.69E-06	0.18	0.28
6	7.3	9.05E-06	0.18	0.24
7	1.1	2.23E-05	0.18	0.44
8	11.8	7.58E-05	0.20	0.51
9	20.5	7.20E-05	0.23	0.35
10	146.1	9.62E-04	0.47*	0.74
11	41.0	1.68E-04	0.15	0.35
12	10.3	1.76E-04	0.18	0.52
13	134.7	9.91E-04	0.23	0.41
14	76.0	6.98E-04	0.24	0.48
15	102.8	7.31E-04	0.27	0.63
16	62.1	1.07E-04	0.26	0.80
17	87.2	6.09E-04	0.21	0.79
18	66.2	1.17E-04	0.15	1.02
19	0.5	3.07E-05	0.23	0.44
20	1.1	5.81E-05	0.24	0.64
21	159.3	2.57E-04	0.23	1.49
22	4.7	3.43E-05	0.21	0.84
23	43.7	1.37E-04	0.22	0.99
24	23.3	1.24E-04	0.25	0.66
25	337.8	1.62E-03	0.24	0.69
26	41.9	1.58E-04	0.15	0.38
27	34.0	1.05E-04	0.18	0.38
28	28.5	1.12E-04	0.20	0.46
29	337.0	4.00E-04	0.38	0.59
30	75.6	2.61E-04	0.35	1.08
31	165.4	3.69E-04	0.14	0.74
32	33.0	2.17E-04	0.18	0.47
33	9.0	1.72E-04	0.18	0.68
34	48.6	1.93E-04	0.20	1.00
35	68.5	1.70E-04	0.19	0.28

References

Angulo-Jaramillo, R., Vandervaere, J.P., Roulier, S., Thony, J.L., Gaudet, J.P., and Vauclin, M. 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers. A review and recent developments. Soil and Tillage Research 55(1/2): 1-29.

Ares, A., and Fownes, J.H. 2000. Productivity, nutrient and water-use efficiency of *Eucalyptus saligna* and *Toona ciliata* in Hawai'i. Forest Ecology and Management 139: 227-236.

Ares, A., and Fownes, J.H. 2001. Productivity, resource use, and competitive interactions of *Fraxinus uhdei* in Hawai'i uplands. Canadian Journal of Forestry Research 31: 132-142

Ben-Dor, E., and Banin, A. 1989. Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method. Communications in Soil Science and Plant Analysis 20(15&16): 1675-1695.

Bonsu, M. 1993. Field determination of sorptivity as a function of water content using a tension infiltrometer. Journal of Soil Science 44(3): 411-415.

Brandt, G.G. 1969. Water movement in hydrophobic soils. *In* Water-Repellent Soils. Proceedings of the symposium on water-repellent soils, May, 1968. eds. L.F. DeBano and J. Letey. University of California, Riverside p. 91-115.

Bryan, L.W. 1957. Tree farming in Hawai'i. 10 p.

Buck, M.G., and Imoto, R.H. 1982. Growth of 11 introduced species on selected forest sites in Hawai'i. Research Paper PSW-169. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture: 12 p.

Buck, M.G., Branam, J.M., Stormont, W.T., and Costales, P.G. 1988. The multiresource forest inventory for Oahu, Hawai'i. Resource Bulletin. PNW-RB-155. Portland, OR: Pacific Northwest Research Station. Forest Service, U.S. Department of Agriculture: 35 p.

Burgan, R.E. 1971. A spacing trial in tropical ash ... an interim report. Research Note PSW-226. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station. Forest Service, U.S. Department of Agriculture: 3 p.

Burk, A.R., Chanasyk, D.S., and Mapfumo, E. 1999. Influences of land disturbance and management regime on infiltration and runoff. Canadian Agricultural Engineering 41(3): 127-134.

Cannell, M.G.R. 1999. Environmental impacts of forest monocultures: water use, acidification, wildlife conservation, and carbon storage. New Forests 17: 239-262.

Cline, M.G., Ayres, A.S., Crosby, W., Philipp, P.F., Elliott, R., Magistad, O.C., Ripperton, J.C., Hosaka, E.Y., Takahashi, M., Sherman, G.D., and Wentworth, C.K. 1955. Soil survey of the territory of Hawai'i. Washington. U.S. Department of Agriculture; Soil Survey Series 1939, no. 25, 644 p.

Cook, F.J., and Broeren, A. 1994. Six methods for determining sorptivity and hydraulic conductivity with disc permeameters. Soil Science 157(1): 2-11.

Crabb, T.B., Allen, J.E., and Whitesell, C.D. 1981. Project: Eucalyptus plantations for energy production in Hawai'i. 1981 Annual Report. Jan. 1981 - Dec. 1981. BioEnergy Development Corporation. Hilo, HI. 196 p.

Crosby, W. 1953. Forestry in the 49th state. American Forests 59(7): 20-22, 43-45.

Cuddihy, L.W. and Stone, C.P. 1990. Alterations of Native Hawaiian Vegetation. Effects of Humans, Their Activities and Introductions. University of Hawai'i Press, Honolulu, HI. 138 p.

D'Antonio, C.M., Hughes, R.F., Mack, M., Hitchcock, D., and Vitousek, P.M. 1998. The response of native species to removal of invasive exotic grasses in a seasonally dry Hawaiian woodland. Journal of Vegetation Science 9(5): 699-712.

DeBano, L.F. 1969a. Observations on water-repellent soils in western United States. *In* Water-Repellent Soils. Proceedings of the symposium on water-repellent soils, May, 1968. eds. L.F. DeBano and J. Letey. University of California, Riverside pp 17-29.

DeBano, L.F. 1969b. Water movement in water-repellent soils. *In* Water-Repellent Soils. Proceedings of the symposium on water-repellent soils, May, 1968. eds. L.F. DeBano and J. Letey. University of California, Riverside p. 61-89.

Degener, O. 1937. Flora Hawaiiensis or New illustrated flora of the Hawaiian Islands, fam. 169a. Acacia confusa. Published privately, Honolulu, 2 p. Rep., 1946.

Dekker, L.W., and Ritsema, C.J. 1996. Uneven moisture patterns in water repellent soils. Geoderma 70: 87-99.

Dekker, L.W., and Ritsema, C.J. 2000. Wetting patterns and moisture variability in water repellent Dutch soils. Journal of Hydrology 231-232: 148-164.

Deuchars, S.A., Townend, J., Aitkenhead, M.J., FitzPatrick, E.A. 1999. Changes in soil structure and hydraulic properties in regenerating rain forest. Soil Use and Management 15: 183-187.

Doerr, S.H., Shakesby, R.A., and Walsh, P.D. 1996. Soil hydrophobicity variations with depth and particle size fraction in burned and unburned *Eucalyptus globulus* and *Pinus pinaster* forest terrain in the Agueda Basin, Portugal. Catena 27: 25-47.

Doerr, S.H., Shakesby, R.A., and Walsh, P.D. 1998. Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. Soil Science 163(4): 313-324.

Donkin, M.J. 1991. Loss-on-ignition as an estimator of soil organic carbon in A-horizon forestry soils. Communications in Soil Science and Plant Analysis 22(3&4): 233-241.

Doughty, R.W. 2000. The *Eucalyptus*: A Natural and Commercial History of Gum Trees. ed. S. Davies. The John Hopkins University Press, Baltimore, Maryland. 237 p.

Dunne, T., and Leopold, L.B. 1978. Water in Environmental Planning. W.H. Freeman and Company. San Francisco CA. 818 p.

Dunne, T., Zhang, W., and Aubry, B.F. 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resources Research 27(9): 2271-2285.

Elsenbeer, H., Cassel, K., and Castro, J. 1992. Spatial analysis of soil hydraulic conductivity in a tropical rain forest catchment. Water Resources Research 28(12): 3201-3214.

Evans, R. 1980. Mechanics of water erosion and their spatial and temporal controls: an empirical viewpoint. In M.J. Kirkby and R.P.C. Morgan (eds), Soil Erosion. Chichester, Wiley: pp. 109-128.

Ewers, B., Binkley, D., and Bashkin, M. 1996. Influence of adjacent stand on spatial patterns of soil carbon and nitrogen in Eucalyptus and Albizia plantations. Canadian Journal of Forest Research 26: 1501-1503.

Famiglietti, J.S., Rudnicki, J.W., Rodell, M. 1998. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. Journal of Hydrology 210(1/4): 259-281.

Foote, D.E., Hill, E.L., Nakamura, S., and Stephens, F. 1972. Soil Survey of Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawai'i. Soil Conservation Service, U.S. Department of Agriculture. 232 p. illus.

Franco, C.M.M., Clarke, P.J., Tate, M.E., and Oades, J.M. 2000. Hydrophobic properties and chemical characterization of natural water repellent materials in Australian sands. Journal of Hydrology 231-232: 47-58.

Frierson, B.B. 1973. A study of the land use and vegetation change: Honouliuli, 1790 - 1925. Unpublished report. Hawaiian Collection, Hamilton Library, University of Hawai'i, Honolulu. 19 p.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A. 1986. Rainfall atlas of Hawai'i. Rep. R-76. Department of Land and Natural Resources, Division of Water and Land Development, State of Hawai'i, Honolulu. 267 pp.

Giambelluca, T.W, Lau, L.S., Fok, Y., and Schroeder, T.A. 1984. Rainfall frequency study for Oahu. Report R – 73. University of Hawai'i Water Resources Research Center, Honolulu, HI. 34 p.

Giffard, W.M. 1913. Some observations on Hawaiian forests and forest cover in their relation to water supply. Presented to Joint Committee on Forestry of the Hawaiian Sugar Planters' Association and the Territorial Board of Agriculture and Forestry. Honolulu, HI. 24 p.

Gill, L.T. 1989. Honouliuli Forest Reserve view plane analysis. A naturalist's view of Hawai'i series. Moanalua Gardens Foundation. Honolulu, HI. 9 p.

Hall, W.L. 1904. The forests of the Hawaiian Islands. Bureau of Forestry, U.S. Department of Agriculture, Bulletin 48, 29 p.

Hamilton, L.S., and King, P.N. 1983. Tropical Forested Watersheds: Hydrologic and Soils Response to Major Uses or Conversions. Westview Press, Inc. Boulder, Co 168p.

Harrington, R.A., and Ewel, J.J. 1997. Invasibility of tree plantations by native and non-indigenous plant species in Hawai'i. Forest Ecology and Management. Special Issue 99(1/2): 153-162.

Horton, R.E. 1933. The role of infiltration in the hydrologic cycle, EOS, Transactions of the American Geophysical Union 14: 446-460.

Hussain, S.B., Skau, C.M., Bashir, S.M., and Meeuwig, R.O. Infiltrometer studies of water-repellent soils on the east slope of the Sierra Nevada. *In* Water-Repellent Soils. Proceedings of the symposium on water-repellent soils, May, 1968. eds. L.F. DeBano and J. Letey. University of California, Riverside p. 127-131.

Joel, A., and Messing, I. 2000. Application of two methods to determine hydraulic conductivity with disc permeameters on sloping land. European Journal of Soil Science 51: 93-98.

Judd, C.S. 1918. Forestry as applied in Hawai'i. The Hawaiian Forester and Agriculturist 15(5): 117-133.

Judd, C.S. 1926. The Natural Resources of the Hawaiian Forest Regions and Their Conservation. 8 p.

Judd, C.S. 1931. Forestry in Hawai'i for water conservation. Journal of Forestry 29(3): 363-376.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., and Schuman, G.E. 1997. Soil quality: a concept, definition, and framework for evaluation. *In* The Soil Quality Institute, ed. The Soil Quality Concept. USDA, Natural Resources Conservation Service, p. 39-49.

Kidron, G.J., Yaalon, D.H., and Vonshak, A. 1999. Two causes for runoff initiation on microbiotic crusts: hydrophobicity and pore clogging. Soil Science 164(1): 18-27.

Larson, W.E., and Clapp, C.E. 1984. Effects of organic matter on soil physical properties. Organic Matter and Rice. p. 363-385, International Rice Research Institute, Los Banos, Laguna, Philippines.

Larson, W.E., and Pierce, F.J. 1991. Conservation and enhancement of soil quality. *In* Evaluation for Sustainable Land Management in the Developing World. Vol. 2. IBSRAM Proc. 12 (2). Bangkok, Thailand. International Board for Soil Research and Management, p. 175-203.

Liang, J., Zhang, J., Chan, G.Y.S., and Wong, M.H. 1999. Can differences in root responses to soil drying and compaction explain differences in performance of trees growing on landfill sites? Tree Physiology 19: 619-624.

Little, E.L., and Skolmen, R.G. 1989. Common Forest Trees of Hawai'i (native and introduced). USDA, Forest Service, Agricultural Handbook no. 679, Washington, D.C. 321 p.

Loumeto, J.J., and Huttel, C. 1997. Understory vegetation in fast-growing tree plantations on savanna soils in Congo. Forestry Ecology and Management 99: 65-81.

Lubker, F. 1886. The wattle trees. The Planters' Monthly. Hawai'i 6(9): 229-230.

Lugo, A.E. 1997. The apparent paradox of reestablishing species richness on degraded lands with tree monocultures. Forest Ecology and Management 99: 9-19.

Lyon, H.L. 1929. Ten years in Hawaiian forestry. The Hawaiian Planters' Record 33 (1): 54-97.

Maxwell, W. 1898. The Hawaiian Islands. Reprint form Yearbook of Department of Agriculture for 1898. 563-582 p.

McCall, W.W. 1975. Soil classification in Hawai'i. Cooperative Extension Service, Circular 476, University of Hawai'i, HI 32 p.

Merriam-Webster, A. 1976. Webster's Third New International Dictionary of the English Language Unabridged. eds. P.B. Gove and The Merriam-Webster editorial staff. G. and C. Merriam Company, Springfield, MA 2662 p.

Minasny, B., and McBratney, A.B. 2000. Estimation of sorptivity from disc-permeameter measurements. Geoderma 95: 305-324.

Morgan, R.P.C. 1995. Soil Erosion and Conservation. Longman Group Limited, Essex, England.

Morin, J., and Kosovsky, A. 1995. The surface infiltration model. Journal of Soil and Water Conservation 50(5): 470-476.

Nakaya, N., and Motomura, S. 1984. Effects of organic and mineral fertilization on soil physical properties and hydrophobicity of soil organic matter. Organic Matter and Rice. International Rice Research Institute, Los Banos, Laguna, Philippines. p. 387-398.

Nelson, R.E. 1967. Records and maps of forest types in Hawai'i. Resource Bulletin PSW-8. Berkeley, CA: Forest Service, U.S. Department of Agriculture 22 p.

Nelson, R.E., Wong, W.H.C. Jr., and Wick, H.L. 1968. Plantation timber on the island of Oahu - 1966. Resource Bulletin PSW-10. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture: 52 p.

Parrotta, J.A. 1992. The role of plantation forests in rehabilitating degraded tropical ecosystems. Agriculture, Ecosystems, and Environment 41: 115-133.

Parrotta, J.A., Turnbull, J.W., and Jones, N. 1997. Catalyzing native forest regeneration on degraded tropical lands. Forestry Ecology and Management 99: 1-7.

Perroux, K.M., and White, I. 1988. Designs for disc permeameters. Soil Science Society of America Journal 52(5): 1205-1215.

Poore, M.E.D., and Fries, C. 1985. The ecological effects of eucalyptus. FAO Forestry Paper 59. Rome, Italy: Food and Agriculture Organization of the United Nations 87 p.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., and Shirmohammadi, A. 1993. Infiltration and soil water movement. In: D.R. Maidment (Editor), Handbook of Hydrology. McGraw-Hill, Inc., New York. P. 5.1-5.51.

Rawls, W.J., Gimenez, D., and Grossman, R. 1998. Use of soil texture, bulk density, and slope of the water retention curve to predict saturated hydraulic conductivity. Transactions of the American Society of Agricultural Engineers 41(4): 983-988.

Rhoades, C., and Binkley, D. 1996. Factors influencing decline in soil pH in Hawaiian *Eucalyptus* and *Albizia* plantations. Forest Ecology and Management 80: 47-56.

Rhodes, E.R., Kamara, P.Y., and Sutton, P.M. 1981. Walkley-Black digestion efficiency and relationship to loss on ignition for selected Sierra Leone soils. Soil Science Society of America Journal 45(6): 1132-1135.

Ritsema, C.J., Dekker, L.W. 2000. Preferential flow in water repellent sandy soils: principles and modeling implications. Journal of Hydrology 231-232: 308-319.

Ruangpanit, N. 1985. Percent crown cover related to water and soil losses in Mountainous forest in Thailand. *In* Soil Erosion and Conservation. ed. S.A. El-Swaify, W.C. Moldenhauer, and A. Lo. Soil Conservation Society of America, Ankeny, Iowa, pp. 462-471.

Sahara, T., Murabayashi, E.T., Ching, A.Y., DeVight, G.D., Fujimura, F.N., Awai, E.L., Nishimoto, L.S., and Baker, H.L. 1972. Detailed Land Classification – Island of Oahu. Land Study Bureau no. 11, University of Hawai'i, Honolulu, 314 p.

Sanchez, P.A., Palm, C.A., Davey, C.B., Szott, L.T., and Russell, C.E. 1985. Trees as soil improvers in the humid tropics? *In* Attributes of Trees as Crop Plants. Eds. Cannell, M.G.R. and J.E. Jackson. Institute of Terrestrial Ecology, Huntingdon, England. 327-358.

SAS Institute Inc. 1999. StatView: StatView Reference. Third Edition. Cary, NC, 528 p

Schubert, T.H., and Whitesell, C.D. 1985. Species trials for biomass plantations in Hawai'i: a first appraisal. Research Paper PSW-176. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture 13 p.

Schuyler, J.D., and Allardt, G.F. 1889. Report on water supply for irrigation on the Honouliuli and Kahuku Ranchos, island of Oahu, Hawaiian Islands. Culture of Sugar Cane. Oakland, CA. 32 p.

Seybold, C.A., Mausbach, M.J., Karlen, D.L., and Rogers, H.H. 1996. Quantification of soil quality. *In* The Soil Quality Institute, ed. The Soil Quality Concept. USDA, Natural Resources Conservation Service, pp. 53-68.

Simunek, J., Wendroth, O., and van Genuchten, M.T. 1999. Estimating unsaturated soil hydraulic properties from laboratory tension disc infiltrometer experiments. Water Resources Research 35(10): 2965-2979.

Skolmen, R. G. No Date. Plantings on the forest reserves of Hawai'i: 1910-1960. Institute of Pacific Island Forestry. Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Honolulu, HI. 441 p.

Skolmen, R.G. 1962. Forests and forest products in Hawai'i - past, present, and future. Pacific Southwest Forest and Range Experiment Station. Berkeley, CA. 3 p.

Skolmen, R.G. 1974. Some woods of Hawai'i ... properties and uses of 16 commercial species. General Technical Report PSW-8. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture 30 p.

Smith, C.W. 1985. Impact of alien plants on Hawai'i's native biota. *In* Hawai'i terrestrial ecosystems; preservation and management. Edited by C.P. Stone and J.M. Scott. Cooperative Park Studies Unit, University of Hawai'i, Honolulu. pp.180-250.

Sobieraj, J.A., Elsenbeer, H., Coelho, R.M., and Newton, B. 2002. Spatial variability of soil hydraulic conductivity along a tropical rainforest catena. Geoderma 108: 79-90.

Sullivan, M., Warwick, J.J., and Tyler, S.W. 1996. Quantifying and delineating spatial variations of surface infiltration in a small watershed. Journal of Hydrology 181: 149-168.

The Nature Conservancy. 2000. Honouliuli Preserve Master Plan.

Tromble, J.M., Renard, K.G., and Thatcher, A.B. 1974. Infiltration for three rangeland soil-vegetation complexes. Journal of Range Management 27(4): 318-321.

US Soil Conservation Service. 1972. Hydrology, National Engineering Handbook Section 4, Washington, D.C.

Viessman, W. Harbaugh, T.E., and Knapp, J.W. 1972. Introduction to Hydrology. ed. R.C. Brinker, Intext Educational Publishers, New York, 415 p.

Wagner, W.L., Herbst, D.R., and Sohmer, S.H. 1999. Manual of the flowering plants of Hawai'i. (ed.) S.W. Mill. University of Hawai'i Press and Bishop Museum Press, Honolulu. 1919 p.

Walker, T.R. 1887. Report of committee on forestry. The Planters' Monthly. Hawai'i 6(11): 531-533.

Walters, G.A., and Wick, H.L. 1973. Coppicing to convert cull Australian toon, tropical ash to acceptable trees. Pacific Southwest Forest and Range Experiment Station. USDA Forest Service Research Note PSW-283. Berkeley, CA. 4 p.

Ward, R.C., and Robinson, M. 1990. Principles of Hydrology. Third Edition. McGraw-Hill Book Company. London, England, 365 p.

Waterloo, M.J. 1994. Soil characteristics of study sites. *In* Water and Nutrient Dynamics of *Pinus caribaea* Plantation Forests on Former Grassland Soils in Southwest Viti Levu, Fiji. pp. 57-86, Academisch Proefschrift, Vrije Universiteit. Geboren te Oranjestad, Aruba.

White, I., Sully, M.J., and Perroux, K.M. 1992. Measurement of surface-soil hydraulic properties: Disk permeameters, tension infiltrometers, and other techniques. Pp. 69-103 *In* G.C. Topp, W.D. Reynolds, and R.E. Green, eds. Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. Soil Science Society of America Special Publication 30.

Whitesell, C.D., and Walters, G.A. 1976. Species adaptability trials for man-made forests in Hawai'i. Research Paper PSW-118. Berkeley, CA: Pacific Southwest Forest and Range Experimental Station, Forest Service, U.S. Department of Agriculture 30 p., illus.

Whitesell, C.D., Wick, H.L., and Honda, N. 1971. Growth response of a thinned tropical ash stand in Hawai'i ...after 5 years. Research Note PSW-227. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station. Forest Service, U.S. Department of Agriculture: 3 p.

Whitesell, C.D., DeBell, S., Schubert, T.H., Strand, R.F., and Crabb, T.B. 1992. Short-rotation management of *Eucalyptus*: guidelines for plantations in Hawai'i. General Technical Report PSW-GTR-137. Albany, CA: Pacific Southwest Research Station. Forest Service, U.S. Department of Agriculture 30 p.

Wiersum, K.F. 1985. Effects of various vegetation layers in *Acacia auriculiformis* forest plantation on surface erosion in Java, Indonesia. *In* Soil Erosion and Conservation. ed. S.A. El-Swaify, W.C. Moldenhauer, and A. Lo. Soil Conservation Society of America, Ankeny, Iowa, pp.79-89.

Williams, J. and Bonell. 1988. The influence of scale of measurement on the spatial and temporal variability of the Philip infiltration parameters - an experimental study in an Australian Savannah woodland. Journal of Hydrology 104: 33-51.

Wood, H.B. 1971. Land use effects on the hydrologic characteristics of some Hawai'i soils. Journal of Soil and Water Conservation 26(4): 158-160.

Wood, H.B. 1977. Division S-7 - Forest and range soils. Hydrologic differences between selected forested and agricultural soils in Hawai'i. Soil Science Society of America Journal 41(1): 132-136.

Yamamoto, T. 1963. Soil moisture constants and physical properties of selected soils in Hawai'i. Research Paper PSW-P2. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station. Forest Service, U.S. Department of Agriculture 10 p.

Yamamoto, T., and Anderson, H.W. 1967. Erodibility indices for wildland soils of Oahu, Hawai'i, as related to soil forming factors. Water Resources Research 3(3): 785-798.

Ziegler, A.D. and Giambelluca, T.W. 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. Journal of Hydrology 196: 204-229.

Ziegler, A.D. and Giambelluca, T.W. 1998. Influence of revegetation efforts on hydrologic response and erosion, Kaho'olawe Island, Hawai'i. Land Degradation and Development 9: 189-206.

Zobel, B.J., Van Wyk, G., and Stahl, P. 1987. Growing Exotic Forests. John Wiley and Sons, New York. 508 p.

Zschokke, T.C. 1930. A Manual for Tree Planters in the Hawaiian Islands. Extension Bulletin 5. Honolulu, HI: University of Hawai'i Agriculture Extension Service 50 p.