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Agronomic qualities of *Pennisetum clandestinum* in association with *Acacia koa* for the mitigation of the effects of ranching and promotion of conservation in a silvopastoral context on the island of Maui, Hawaii

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***MAGISTER SCIENTIAE* IN AGROFORESTRY AND SUSTAINABLE AGRICULTURE**

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Resumen

Los bosques hawaianos mésicos de altura han sido transformados por la ganadería y ungulados invasores durante los últimos 200 años. La flora y fauna de las islas hawaianas han sido radicalmente alteradas por la introducción de especies invasoras, incluyendo el ganado. Existe un grupo de personas en las islas que apoyan para la reintroducción de y reforestación con especies nativas, además una parte de agroecólogos están interesados en la reforestación en espacios agrícolas. Los desafíos económicos y logísticos en la industria ganadera, combinados con el aumento en condiciones de sequía, han creado tiempos difíciles. Por lo tanto, más fincas ahora están investigando y considerando los servicios ecosistémicos que proporcionan los árboles en las explotaciones ganaderas.

Una de las especies clave de las islas hawaianas es el árbol endémico Acacia koa, que es conocido por su valiosa madera e importancia cultural, capacidad de fijar nitrógeno, recarga de acuíferos y usos en agroforestería. Se ha investigado bastante esta especie en la isla grande de Hawái. No obstante, todavía existe mucha información por aprender sobre variedades de A. koa en la isla de Maui y cómo utilizarlas en sistemas silvopastoriles.

En el presente trabajo se analiza la relación entre la especie arbórea A. koa y la gramínea Pennisetum clandestinum (kikuyu) en un contexto silvopastoril a 1585 msnm en la isla de Maui, Hawái. El sitio de investigación se llama Pu'u Makua y se ubica en la falda suroeste de la montaña Haleakalā (3055 msnm) y es parte del Rancho Ulupalakua. Se tomó un total de 28 muestras de forraje kikuyu en la época seca, por lo cual 21 fueron muestreados bajo doseles de A. koa (que fueron plantados a 3, 4 y 6 m de distancia). Las otras siete muestras fueron tomadas a pleno sol (donde no existían árboles de A. koa). Este mismo protocolo (muestreo de n=28) fue repetido en la época lluviosa. Las muestras de forraje fueron enviadas al laboratorio de diagnóstico agrícola de la Universidad de Hawái en Manoa para comparar los atributos del kikuyu bajo varias densidades de sombra de A. koa y a pleno sol. Para entender mejor el Índice de Área Foliar (LAI, por sus siglas en inglés) del dosel de varias densidades de A. koa, se tomaron fotos hemisféricas (de 180º) que después fueron subidas al software Gap Light Analyzer. Los datos de LAI de A. koa y también atributos del forraje P. clandestinum después fueron subidos al software estadístico InfoStat para investigar relaciones entre cobertura de dosel y calidad de forraje en cada sitio específico. Se hicieron mediciones de los árboles de A. koa para estimar el carbono secuestrado y estimar el potencial maderable de esta especie, por si el Rancho Ulupalakua decide vender créditos de carbono o cosechar de manera sostenible. También se encontró tras análisis de correlación Pearson que existen relaciones estadísticamente significativas entre A. koa y la calidad del forraje kikuyu.

La última etapa de este trabajo de investigación fue entender a profundidad el conocimiento de los ganaderos en la isla de Maui acerca de este tema. Se hicieron encuestas sobre las percepciones de varios ganaderos de árboles nativos e invasoras y sus rasgos para sistemas silvopastoriles. Los ganaderos también identificaron especies que fueron útiles (o dañinas) a sus operaciones y a la salud del ganado. Como resultado, se compiló una lista de especies arbóreas y sus efectos sobre operaciones de *fincas en elevaciones altas en Hawái. A. koa estaba en esa lista de árboles útiles y también confirió varios servicios ecosistémicos y beneficios a P. clandestinum. Por lo tanto, se sugiere la incorporación de A. koa en sistemas ganaderos en la isla de Maui en sitios apropiados. Se requiere más investigación detallada para confirmar los resultados preliminares de este trabajo de investigación.*

Palabra claves: Fijación de nitrógeno, índice de área foliar, kikuyu, koa, secuestro de carbono

Abstract

Upper-elevation mesic Hawaiian forests have been transformed by cattle ranching and wild (invasive) ungulates within the past 200 years. Although the flora and fauna of the Hawaiian Islands have been radically altered by the introduction of invasive species, there is a movement of agriculturalists within the islands interested in reintroducing native species and reforesting with them in agricultural spaces. Current economic and logistical challenges to the ranching industry, combined with increases in drought conditions, have created challenging times for the ranching community. Therefore, more ranches are now investigating and considering the ecosystem services of trees and potential for silvopastoral systems within the ranching landscape. One of the keystone species in the Hawaiian Islands is the endemic tree species Acacia koa, known for its valuable wood and cultural importance. This species is also valuable for nitrogen fixation, aquifer recharge, habitat for biodiversity and usefulness in agroforestry systems. While investigation into the species has been done on the Big Island of Hawaii, there is much to be learned about the variants of A. koa on the island of Maui as they relate to the potential for silvopastoral systems.

This investigation is focused on the relationship between the tree species A. koa and the forage grass species Pennisetum clandestinum (kikuyu) in a silvopastoral context, at an elevation of 5,200 feet above sea level (1585 masl) on the island of Maui. The site of investigation is called Pu'u Makua in Hawaiian and is situated on the southwestern flank of Haleakalā (10,023 feet above sea level–3055 masl) and is part of Ulupalakua Ranch. A total of n=28 forage samples of P. clandestinum were taken in dry season, 21 of which were taken from underneath the canopies of koa trees (which had been planted in densities of 3, 4 and 6 m apart). The other seven samples were taken in full sun (where no koa trees were growing). This same protocol (sampling n=28) was repeated in the wet season. Forage samples were then sent to the Agricultural Diagnostics Laboratory at the University of Hawai'i at Manoa for forage analysis to compare attributes of kikuyu under different canopy densities of A. koa. To better understand the leaf area index (LAI) of the canopy of various densities of A. koa, hemispheric (180 degree) photos were taken and then input into Gap Light Analyzer Software for LAI. LAI data of A. koa as well as forage attributes of P. clandestinum were then input into the statistical software InfoStat to investigate relationships between canopy cover and forage quality at each specific location. It was found through Pearson correlation analysis that there are in fact significant relationships between koa and the quality of kikuyu. Measurements of koa trees were also taken to estimate the amount of carbon *sequestered within each tree and estimate woody biomass in this lumber-producing species in case Ulupalakua Ranch were to decide to sell carbon credits or sustainably harvest koa in future projects.*

Lastly, to better understand the knowledge of ranchers on Maui, we conducted surveys regarding various ranchers' perceptions of native and non-native trees and their usefulness for silvopastoral ranching systems. Ranchers also identified various tree species that were of use (or harmful) to their ranching operations and to the health of the herd. As a result, a list of tree species helpful or harmful to ranching operations in high-elevation Hawaii ranches was compiled. Since A. koa was on this list of helpful trees and conferred various ecosystem services and benefits to P. clandestinum, the incorporation of koa into ranching systems on the island of Maui is recommended in zones appropriate for its growth. Further detailed investigation is required to confirm the preliminary findings of this project.

Key Words: Carbon sequestration, leaf area index, kikuyu, koa, nitrogen fixation

1 INTRODUCTION

1.1 Background

The Hawaiian Islands have seen a precipitous loss of forest cover and endemic species due to cattle ranching and invasive ungulate species such as goats and deer. With less than 10% of their original distribution remaining, dryland forests of Hawaii still serve as an important refuge for many endemic species and cultural resources (Medeiros *et al.* 2014). On a global scale, a loss in forest cover due to conventional ranching has precipitated a loss in topsoil, increased erosion, decreased agricultural productivity and a negative impact on the health of watersheds (Köhl et al. 2015). The leeward slopes of Maui, Hawaii, have not been unaffected by conventional ranching practices, which have promoted deforestation since the first introduction of cattle by Captain George Vancouver in 1793 (Maly *et al.* 2000). The existence of feral goats, pigs and deer *(Axis axis)* have further exacerbated deforestation. Various conservation projects have sought to restore native Hawaiian forests but invasive species have complicated the process.

Noncommercial projects promoting native reforestation and conservation are of great importance, but in areas still experiencing cattle grazing, mixed-use traditional silvopastoral systems may both mitigate the environmental impacts of ranching and promote conservation (Harvey *et al.* 1999), augmenting sustainable production to the extent that more lands can be utilized for conservation efforts because of increased efficiency in land use (Kantor 1999). It has been proven in some parts of Central America that ranchers can experience an increase of up to 30% in livestock productivity with the implementation of silvopastoral practices (Ibrahim *et al.* 2010). A silvopastoral system in the context of a tropical climate can be defined as *the integration of trees and shrubs in pastures with animals for economic, ecological and social sustainability* (Ibrahim *et al.* 2010). It is possible that the adoption of practices implemented in tropical Latin America could have similar results in Hawaii and spur a faster rate of reforestation as well as encourage the protection of remnant trees and forests on converted ranchlands. Leguminous tree species endemic to the Hawaiian Islands, such as *Acacia koa*, have been investigated as a nitrogen-fixing species that could serve as native trees useful in silvopastoral systems (Baker *et al* 2009), but there is still more to discover, particularly on the island of Maui. There is genetic variation in varieties of koa between each island (Daehler *et al.* 1999).

While mature *A. koa* trees and other endemic species can compete with aggressive mechanical and allelopathic competition from *Pennisetum clandestinum*, juvenile trees and the propagation of dormant seeds are negatively affected by this invasive grass. It is for this reason that there are many ¨museum forests¨ on the leeward slopes of Haleakala, composed of trees that existed prior to the arrival of the first cattle, goats and deer in the 1800s.

This thesis project aimed to review the relationship between *P. clandestinum* (kikuyu) and *A. koa* and how availability and nutrient contents of kikuyu can be enriched by the presence of *A. koa* trees within pasturelands, measuring the effect of various densities of *A. koa* trees on the growth and forage qualities of *P. clandestinum.* It also aimed to identify ecosystem services (particularly carbon sequestration) rendered by *A. koa*, along with the potential economic benefits of sustainable forestry.

1.2 Justification

In the restoration of degraded areas, it is necessary to establish areas designated for "partitioned" conservation, in which the final goal is to restore the richness and diversity of species that at one point existed in that site. This involves the exclusion of cattle and other invasive ungulates. Nonetheless, in the Hawaiian Islands, there are ranches that will inevitably still focus on livestock production. For that reason, it is necessary to find strategies that mitigate and reduce the effects of grazing. The inclusion of endemic trees in silvopastoral systems in Hawaii may dampen the effects of erosion, augment soil fertility and increase productivity to the extent that less land could be needed to produce the same amount of cattle.

The inclusion or protection of native tree species in silvopastoral systems has been proven to serve as a biological corridor for the habitat and movement of species (Tobar and Ibrahim 2008). The Hawaiian Islands are some of the most isolated islands on earth and thus are a treasure trove of endemic species. Each one of the Hawaiian Islands is unique and contains its own set of endemic species. One such avian species that has benefited from reforestation with koa has been the 'akiapōlā'au *(Hemignathus munroi).* A study of *A. koa* timber stands on the Big Island of Hawaii showed significant amounts of native birds at these sites, likely due to the increase of habitat as well as insect food sources within the trees. The birds were less territorial within higher densities of koa, suggesting that there was higher food availability within the system (Pejchar *et al.* 2005). Mature koa is particularly important for bird habitat (Whitesell 1990). In addition to the positive effect of *A. koa* on avian species, koa is also known as a foundational species to the health of the Hawaiian forest and the health of other native plants. As of 2018, 484 Hawaiian plant species were on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (approximately 35% of the Hawaiian flora) (IUCN 2018). This highlights the necessity for further protection and promotion of Hawaiian plant species, all of which are home to native fauna.

Just as native species render ecosystem services and contributions to biodiversity, silvopastoral systems can also serve to increase sustainable agricultural production per each unit of land, which is relevant to finite amounts of land where farmers and ranchers work. This increase is even more relevant in the case of the Hawaiian Islands, where land availability is at a premium. This measurable increase in productivity can be explained through a land equivalent ratio, which measures the yields of various crops (in this case, forage and wood) in conjunction, ultimately comparing the productivity of this multiuse system with the yield that would have been seen in monocultures of the aforementioned ¨crops¨ (Kantor 1999). The establishment of silvopastoral systems provides farmers with the options of continuing to produce food while providing benefits for society and the global environment (Ibrahim 2010). There is ample evidence in Central America that reforestation in degraded areas can diminish erosion and ameliorate the effects of heat and drought stress on animals through a greater retention of moisture in organic material and root systems (Ibrahim *et al.* 2005). This reduction of the effects of heat and caloric stress ultimately contributes to the caloric efficiency of cattle and contributes to healthy weight gain. This same increase in productivity could be implemented on working cattle ranches in the Hawaiian Islands, thus reducing the amount of land needed for production and assisting in conservation efforts. This research is also relevant in addressing changes that the agricultural community in Hawaii may see with increases in the frequency and severity of drought, since large-scale production with simplified grass monocultures ¨results in agricultural landscapes that are more vulnerable to climate change and drought¨ (Ibrahim 2010).

1.3 Objectives and Research Questions

1.3.1 *General objective*

To study the availability and forage quality of *Pennisetum clandestinum* in association with the endemic tree *Acacia koa* for the mitigation of the effects of ranching and promotion of conservation in a silvopastoral context on the island of Maui, Hawaii.

1.3.2 *Specific objectives*

1. Determine leaf area index (LAI), volume of wood and carbon in wood in three levels of tree cover of *Acacia koa.*

2. Evaluate the effect of shade cover (and nutrient cycling) of *A. koa* on the availability and quality of the forage grass kikuyu (*Pennisetum clandestinum*).

3. Conduct interviews to investigate the perceptions of Maui ranchers regarding *A. koa* within cattle operations and to formulate proposals for ranching practices that can meet the long-term economic and environmental necessities of the island.

1.3.3 *Research questions*

- What are the levels of shade (measured as LAI) projected onto the pasture in three different densities of tree cover?
- Approximately how much carbon (in tons per hectare) is stored within the three densities of the trees sampled?
- At which density of tree does *P. clandestinum* have the highest availability of forage in Ulupalakua, Maui?
- At which density of tree cover does *P. clandestinum* have a higher forage quality?
- To what extent is forage quality influenced by LAI?
- How do different tree species contribute to ranching practices (shade, forage material or increase in pasture quality)?
- How does *A. koa* affect ranching operations?
- What types of practices would create a win-win scenario for both ranchers and the environment?

1.4 Literature Review and Conceptual Framework

1.4.1 Acacia koa *in the Hawaiian Islands*

Acacia koa A. Gray (koa) is a member of the family Fabaceae, subfamily Mimosoideae, genus *Acacia,* subgenus *Phyllodineae.* (Baker *et al.* 2009) and is endemic to the Hawaiian islands of Hawaii, Molokai, Maui, Lanai, Oahu and Kauai *(*Elevitch *et al.* 2006)**.** The species typically attains heights of 15 to 25 m (50 to 80 ft) with a canopy spread of 6 to 12 m (20 to 40 ft). It grows in a wide elevation range of 100 to 2300 masl (330 to 7500 ft) with annual rainfall of 850 to 5000 mm. Koa is a particularly important member of montane Hawaiian forests (Whitesell 1990).

Beginning in the 1850s, *A. koa* was affected by logging, land clearing and ranching operations (Scowcroft and Jeffrey 1999). Once ungulates such as cattle, goats and wild deer *(Axis axis)* were present in these grasslands, koa had little chance at natural regeneration (Barrera and Kelly 1974). In addition, the introduction of grasses such as the African forage *Pennisetum clandestinum,* which is a C4 species, have dominated pasturelands and significantly decreased the germination and growth of trees (Mears 1970; Wilen and Holt 1996).

Given that context, koa maintenance and reforestation are important for the following reasons:

1. It is an important habitat for native plants and animals.
2. It provides important economic benefits either directly through ecotourism and forestry or indirectly through watershed protection.
3. Koa wood is an important part of Hawaiian culture. It was long associated with Hawaiian royalty and has long been used to build the traditional Hawaiian outrigger canoes for fishing, racing and voyaging (Baker *et al.* 2009).
4. Koa has roles in ecosystem services and economic, ecological and conservation values for communities (Baker *et al.* 2009).

1.4.2 Acacia koa *silviculture and silvopasture in the Hawaiian Islands*

A. koa is a keystone species in the native Hawaiian ethnobotanical toolbox and was traditionally harvested according to strict protocol and sustainable limits (Kamakau 1961). This was particularly important in order to have large enough koa logs for carving canoes. After years of deforestation, so few sizeable koa trees have remained that foresters and the Hawaii Department of Land and Natural Resources have created new policies and incentives for the sustainable harvest of koa (Creamer 2019).

The silvicultural management of *A. koa* has been investigated in various sites in the Hawaiian Islands. Since the heterogeneity in the phenology of koa between different islands and different sites on each island is significant (Sun 1996; Conkle 1997), further investigations are highly relevant. These differences between *A. koa* sub-types, combined with factors of location, have yielded a multitude of allometric equations applicable for estimating woody biomass and carbon sequestration (Baker *et al.* 2009). While most koa silvicultural observations have been in reforestation, commercial plantations and remnant forests, there has been limited research pertaining to the interaction of koa with forage quality and availability in a silvopastoral context. The most significant work done on koa in a silvopastoral context to-date was a doctoral thesis executed on the Big Island of Hawaii (Grace 1995). In Grace's work, he found that there was a significant link between levels of shade of *A. koa* and the composition, availability and quality of *P. clandestinum* at Keauhou Ranch on the Big Island. Grace also found that planting *A. koa* in ranchlands could yield a merchantable quantity of lumber and can be profitable as long cattle are kept away from juvenile trees until they are roughly seven years old (personal communication with Dr. J.B. Friday, 2020). Although cattle ranching has been phased out in the koa groves of Keauhou Ranch, the koa trees remain and have been considered for sustainable harvesting.

Most research regarding *A. koa* silviculture and silvopasture has been conducted on the Big Island of Hawaii since it contains the largest forests in the islands. While this work on Big Island is extremely important and applicable for all islands, it is also relevant to study silvopastoral interactions on the island of Maui given that the width of koa phyllodes is different (Baker *et al.* 2009) and that nutrient levels of leaf litter may be higher in dry or mesic regions (Jenny 1980). Elevation, soil type and topographic relief also play a role in the vigor of koa (Scowcroft and Jeffrey 1999).

Other studies have yielded valuable insight into potential scenarios for economically viable reforestation and conservation on private lands (Goldstein *et al.* 2006). These scenarios were examined in a koa conservation case study, which compared the net present value (NPV) of seven different potential land uses. The study found that while *Timber + Subsidy 1 + Cattle* had a positive mean NPV (USD 596/acre)—exceeding an opportunity cost of only cattle ranching (mean NPV of USD 194/acre), it still had a significantly lower NPV than focusing only on *Timber + Subsidy*, which had a mean NPV of USD 671/acre. At a glance, it would appear that utilizing land solely for timber (with the current state of Hawaii subsidy) would be superior to integrating *Timber + Subsidy + Cattle*. However, *Timber + Subsidy* has a potential for negative cash flow in the beginning stages of the investment, while *Timber + Subsidy + Cattle* has the potential to generate cash flow in the initial years of the project (as long as cattle are prevented from damaging juvenile trees). Any of these options present more potential for profitability than the sale of carbon credits alone, which in fact has a negative NPV, in which the landowner makes significantly less than with just cattle ranching. This highlights the need for integrative land use as well as subidies from government agencies to incentivize reforestation. This same investigation by Goldstein and his colleagues also highlighted the fact that reforestation with *A. koa* is significantly more profitable than for other species of lumber, none of which have the market price or cachet of koa.

1.4.3 A brief history of Hawaiian agriculture in the Ulupalakua region

It is important to understand the cultural and archaeological heritage of the Ulupalakua, Honua'ula and Kahikinui regions to better contextualize agriculture and land use on Maui and in Hawaii. Prior to the arrival of cattle in the Hawaiian Islands in 1793, the leeward slopes of Haleakala, from Kaupo to Kula, were extensively cultivated by Native Hawaiians, who terraced vast areas of land and grew *´uala,* or sweet potato *(Ipomoea batata).* Intergenerational knowledge, combined with contemporary archaeology, has confirmed that Hawaiians living in the area emphasized the cultivation of crops within the swales and depressions of the landscape, which utilized the accumulation of sediment, nutrients and moisture beneficial to root and vegetable crops (Kirch *et al.* 2013). In addition to intensive dryland agriculture, the population surrounding the district of Auwahi sustainably harvested from the dryland forests on the upper slopes of Haleakala (915–1525 masl) for ethnobotanical uses, including for medicine, tool making, canoes, tools for making kapa, weapons, fishing, dyes and religious purposes (Medeiros *et al.* 1998). Upon the arrival of the first Europeans and ungulates, the landscape of Auwahi changed drastically and today only a small fraction of the forest remains. Auwahi is particularly unique in that it contains 13 species on the IUCN Red List of Threatened Species (IUCN 2018), all of which have been negatively affected by invasive species. However, reforestation efforts at Auwahi have been largely effective, with large groups of volunteers replanting endemic species (Medeiros *et al.* 2014).

Following the arrival of the first Europeans, Polynesian agriculture and ethnobotanical practices were highly affected by an array of historical events, including the introduction of the first cattle to Hawaii by the English Captain George Vancouver in 1793. Hawaii developed its own cowboy culture and tradition, predating that of the American West, in response to the powerful impact of cattle on its landscape. The culture and land-management practices of the *paniolo* (Hawaiian cowboy) are key components in the story and contextualization of current-day ranches on Maui and Hawaii islands. Following the arrival of cattle to the Hawaiian Islands, herds quickly multiplied to the extent that wild cattle trampled through forests and gardens, wreaking havoc on the land and population. To control these roving herds, Kamehameha III brought *vaqueros* (Mexican-Spanish cowboys) to Hawaii to teach how to herd (Kuykendall *et al.* 1970). The Hawaiian paniolos who learned from these vaqueros became skilled at roping and riding, with cowboys like Ikua Purdy traveling as far as Cheyenne, Wyoming, where he won the 1908 Frontier Days World´s Steer Roping Championship (Fischer 2007). Since then, ranches have carried on the Hawaiian paniolo tradition, but extended periods of drought, combined with economic headwinds and an increase in mainland beef imports, have made Hawaiian ranching operations more difficult in the past decades.

As in other parts of the world, including but not limited to New Zealand, South Africa, Australia's New South Wales and South America, the C4 forage species *P. clandestinum* (kikuyu) was introduced by ranchers and agronomists to the Hawaiian Islands to increase ranch productivity. It is a key species in all Upcountry Maui ranches, as well as the most prominent upper-elevation ranches on the Big Island of Hawaii. While the introduction of this forage has been largely helpful to ranching operations, the introduction of kikuyu by Maui and Big Island ranches in the early-1900s has also had deleterious effects on forest regeneration and traditional Hawaiian agriculture, since the species has well-documented vigorous reproduction and allelopathic chemical production (Marais 2001). While the grass presents its own set of challenges, it has proven to be good forage for local ranches and provides most forage for Upcountry Maui ranches. In this study, we sought to find a potential win-win scenario in which conservation-friendly silvopastoral ranching practices could be identified. Finding strategies to improve quality and quantity of kikuyu forage is particularly important given that Hawaiian ranches do not finish their herd on grains (USDA 2020).

1.4.4 Maui and Hawaiian beef in general

The Hawaiian beef industry has recently faced challenges from beef imports, periodic drought and even pests such as the two-lined spittlebug, which has decimated some kikuyu pastures on the Big Island of Hawaii (Brestovansky 2019). Despite these challenges, the industry is enjoying an increase in consumer preferences for locally produced grass-fed beef and dairy products. As of January 2020, Hawaiian ranches contained a total of 140,000 cattle and calves, including 75,000 beef cattle that had been calved. While ranches in the continental United States tend to fatten and finish cattle on feed consisting of grains and other caloric inputs, Hawaiian ranches as of 2019 and 2020 had close to 0% cattle on feed, according to inventories produced by the United States Department of Agriculture National Agricultural Statistics Service (USDA 2020). Improved breeding practices have yielded herds that are predominately Brangus *(Bos indicus x Bos taurus)* and Angus *(Bos taurus)*, with ranchers deciding to incorporate Brahman *(Bos indicus)* stock into their herd for increased resiliency to drought and heat. Overall beef production in the islands in 2018 was approximately 7.4 million pounds, which represents a mere 5.8% of the beef consumed in Hawaii (Hawaii Beef Industry Council 2018). This suggests that there is room for island ranches to grow into a larger share of the marketplace. While the acreage of Maui ranches is less than those on the Big Island of Hawaii, these ranches still represent a significant segment of Hawaiian ranching.

Major Upcountry and East Maui ranches represent a total of 22,640 ha (55,945 acres): Kaupo Ranch—1,977 ha (4,887 acres); Kaonoulu Ranch—3,259 ha (8,054 acres); Haleakala Ranch—11,735 ha (29,000 acres); Hana Ranch—1,098 ha (2,715 acres); Ulupalakua Ranch—4,472 ha (11,051 acres) and Hokunui Ranch—96 ha (238 acres) (Maui Tomorrow Foundation 2011).

1.4.5 Benefits of silvopastoral systems for livestock productivity

The main reasons that silvopastoral systems have been promoted include the retention of topsoil, water cycle regulation, nutrient cycling, the conservation of species, carbon sequestration, timber investments and increased efficiencies in animal production (Alavalapati *et al.* 2004). The utilization of trees for windbreaks is particularly important in Hawaiian pasturelands for protection from brisk tradewinds (Friday *et al.* 2017). There are many interactions within silvopastoral systems, which can be positive or negative depending upon the selected species, the density of the canopy, spatial arrangement of the trees and management of the system (Giraldo and Velez 1993). While many tree species can be used, some may not be appropriate for mixed-use systems because they possess allelopathic properties that discourage the growth of forage beneath them— Eucalyptus is an example (El-Rokiek 2009). *A. koa* does not possess strong allelopathic characteristics and is a suitable candidate for use in the ranching landscape. Silvopastoral systems are relatively uncommon in the Hawaiian Islands but have been implemented and investigated on the Big Island of Hawaii (Grace 1995). Grace‘s research showed that the incorporation of *A. koa* within kikuyu pasturelands has the potential for profitable ranching and lumber operations, with productive output from cattle forage and koa within the same areas. Silvopastoral systems have been studied extensively in other parts of the tropics, including in high-elevation pasturelands where the principal forage is *P. clandestinum*. Silvopastoral systems combining other acacia species with pasturelands are not uncommon, given that trees in the acacia family fix nitrogen and enrich the soil. *Acacia decurrens* with *P. clandestinum* has been studied in high-elevation ranches of Colombia, in which investigators found that *A. decurrens* planted in a low density (407 trees/ha) produced the highest output of milk in dairy cows. This exceeded the milk production in areas with a high density of plantings (1,110 trees/ha) and in the control (no trees) (Giraldo and Bolivar 1998).

While silvopastoral systems have proven valuable in upper-elevation regions of the tropics, they are particularly valuable in mitigating the effects of heat and drought on the herd. Mixed-use systems have been especially successful in dry regions of Central America in buffering the effects of long seasonal droughts. In a study carried out in the arid zone of Cañas, Costa Rica, it was shown that the portion of the herd grazing in pastures with a high level of tree cover (27%) gained on average 10.4 kg more (7%) than cattle that had been grazing in pastures with low tree coverage over a one-year period (Restrepo 2004). Increase in animal production can be attributed to improvements of forage availability and quality in such systems (Grace 1995; Giraldo and Bolivar 1996), as well as the increased comfort of the herd grazing in areas protected from the sun and wind. The decrease in caloric expenditures of animals grazing in shaded areas has been proven to help with increased weight gains (Ibrahim *et al*. 2010).

While there are multiple benefits from the incorporation of trees in ranching systems, potential negative trade-offs posed by silvopastoral systems can include increased challenges in the management and herding of cattle in forested areas. There is anecdotal evidence of cattle eating koa seedlings that are less than seven years old and damaging the bark on older trees to the extent that future lumber harvests are compromised.

1.4.6 Benefits of silvopastoral systems for soil conservation

Intact forests are known to have greater water retention and less erosion than degraded pasturelands. It has been proven on the island of Maui that full partition and reforestation of former pasturelands improves soil qualities (Perkins *et al.* 2014). While dispersed trees in pasturelands will not have the same effect as full conservation, it has been proven in other parts of the tropics that livestock production systems that retain and promote trees will have less soil erosion than conventional ranches. In a dry ranching region of Esparza, Costa Rica, it was shown that surface runoff was significantly higher in degraded pastures (42%) compared with perennial forage banks (3%), young secondary forests (6%) and pastures with a high density of trees (12%) (Rios *et al.* 2006). Even individual trees can increase rainwater infiltration through root penetration, organic material and a reduction in the compactation of the soil (Chará *et al.* 2008). These types of benefits are particularly important for leeward Haleakala, which has no perennial streams and in which current groundwater recharge during drought conditions is presumed to be reduced by 37% (Maui County 2018). It is likely that ranching areas in Hawaii could see benefits derived from tree cover in pasturelands similar to that in other parts of the tropics.

1.4.7 *Carbon sequestration of* Acacia koa *and of other* Acacia *species*

Another notable benefit of the retention of trees in ranching systems is carbon sequestration, which can decrease levels of atmospheric carbon and mitigate the effects of climate change. Carbon sequestration occurs in tissues and wood aboveground and in the root masses and humus beneath the soil surface. In Hawaii, it has been shown that native forests created a significantly higher level of live biomass carbon storage than introduced species, or alien plantation species (Selmants *et al.* 2017). In silvopastoral systems in Colombia, Giraldo *et al.* (2006) found that if properly managed, carbon storage was significantly higher than in treeless grazing systems. The establishment of *Acacia* species in conjunction with kikuyu has become increasingly common not only for productivity but also for carbon sequestration. In Hawaii in particular, it has been discovered that the establishment of koa in pasturelands can lead to an increase in soil carbon (C) and nitrogen (N) within 10 years (Baker *et al.* 2009) and that the overall sequestration of carbon is significantly higher than that of invasive grasses (Hughes *et al.* 2017). Besides the benefits of *A. koa* to increases in soil carbon storage, Selmants *et al.* (2016) have recently explored aboveground and root-mass carbon sequestration. These findings quantify the benefits of tree cover and may give landowners the ability to sell carbon credits or receive assistance from nonprofit or government agencies for reforestation efforts. The sequestration of carbon has become increasingly important in recent years, with increased incentives. However, the current market price for carbon is so low that the financial benefit to a ranch does not offset the high cost of reforestation. For that reason, it would be necessary for Hawaiian ranches to pursue additional state incentive programs to produce a positive NPV and could not depend on the sale of carbon credits alone to make reforestation economically viable (Goldstein *et al.* 2006). It should also be noted that cattle introduced into koa stands have the potential to change stand structure and lessen the amount of carbon sequestration. This study sought to identify the biomass of each sampled koa tree as well as estimate the amount of sequestered carbon in various densities.

1.4.8 *Economic potential for the sustainable harvest of koa lumber*

Koa wood is economically valuable and since ancient Hawaiian times has been of great use for the construction of canoes, paddles, housing and various other implements (Bishop Museum 2020). Since the arrival of the first herd of cattle and goats brought by Captain George Vancouver in 1793, many of the formerly vast koa forests have been cleared for cattle ranching (Fischer 2007). While limited private landowners have reforested on a small scale, it has been within the past three decades that the state of Hawaii has created incentives and programs for the reforestation of koa for both conservation and commercial purposes. Great efforts have been made to emphasize the sustainable harvest of koa, with state and conservation easements only harvesting from dead or dying trees (Creamer 2019). With a relative decrease in supply and a great increase in demand, the price of koa has skyrocketed in recent years, with prices for common-grade koa selling for USD 30/board foot and curly instrument-grade koa selling for as much as USD 125/ board foot (personal correspondence with Brian Green of Pacific American Lumber 2020). With such high prices, landowners, including ranchers in high-elevation regions of Maui and the Big Island, have begun to consider koa timber plantations and the incorporation of *A. koa* into silvopastoral systems as a way of increasing the financial viability of their operations. Various scenarios for land management with koa were weighed against each other in a study by Goldstein *et al*. (2006**),** in which investigators considered the NPV of koa-growing systems. They found that with current prices, land values, taxes and government incentives/subsidies, it made the most financial sense to focus exclusively on the growth of koa in a plantation or conservation setting, simultaneously excluding ungulates from the operation. Nonetheless, their project verified that silvopastoral ranching systems incorporating *A. koa* have a positive NPV, particularly if cattle were excluded from the area in which the juvenile trees were planted for a minimum of seven years to let the trees reach an adequate size (personal communication with Dr. J.B. Friday, head extension forester of the state of Hawaii, 2020).

Literature from *A. koa* silvopasture on the Big Island elucidates some of the benefits and potential pitfalls of integrating koa and kikuyu. In his study on the modeling of koa growth within *P. clandestinum* pasturelands at Keauhou Ranch, Grace (1995) found that ¨grazing of koa early in stand development reduced leaf area index and harvestable volumes but allowed greater grass production.¨ Young koa was extremely vulnerable to grazing from cattle, and any opportunities for merchantable timber were greatly reduced by introduction of the herd in the early stages of koa growth. Modeling used in the Big Island study also highlighted the difficulty of estimating the marketable volume of timber harvests, given that it is not correlated with average tree size or total stand biomass but rather size-class distribution within stands.

The *A. koa* trees within much of the system at Pu'u Makua at Ulupalakua Ranch on Maui are not yet of harvestable age and size and are unlikely to be harvested since they are part of a conservation easement. Nonetheless, *A. koa* planted in an adjacent grazing area would grow at a similar form and rate. Trees in zone 2 were planted about 2001, yet we would still not be able to produce an estimate of merchantable timber based upon a sample size of n=7 and without destructive sampling. The diameter at breast height of the sampled koa from zone 2 trees ranged from 9.20 to 35 cm (see Figure 6, in section 2.3.3), and height to the first fork was measured. Allometric equations based upon Maui *A. koa* were applicable for estimates of carbon sequestration and could be considered for merchantable timber once the trees are larger (Conrad 2005).

Koa sapwood has very little economic value, while koa heartwood is of great merchantable value. It is difficult (and inaccurate) to estimate merchantable heartwood at any given site without destructive sampling, which would involve taking destructive samples of trees (personal correspondence with Nicklos Dudley, University of Hawaii forester, September 30, 2019). Without a greater frame of reference, we would still suggest planting koa at 3 m and then selectively thin trees to estimate heartwood. Given that it would be difficult to estimate future timber harvests for this particular site without destructive sampling, it is useful to refer to established literature showing the potential profitability of *A. koa* in a silvopastoral context. Multiple land-use scenarios were examined in a koa conservation case study (Goldstein *et al.* 2006), which compared the NPV (USD/ha) of seven different potential land uses. The study found that while *Timber + Subsidy 1 + Cattle* had a positive mean NPV (USD 1,466.16/ha) exceeding an opportunity cost of ranching cattle only (mean NPV of USD 477.24/ha), it still had a significantly lower NPV than focusing only on *Timber + Subsidy*, which had a mean NPV of USD 1,650.66/acre. At a glance, it would appear that using land solely for timber (with the current state of Hawaii subsidy) would be superior to integrating *Timber + Subsidy + Cattle*. However, *Timber + Subsidy* has a potential for negative cash flow in the beginning stages of the investment, while *Timber + Subsidy + Cattle* has the potential to generate cash flow in the initial years of the project (as long as cattle are prevented from damaging juvenile trees).

1.5 Methodology

1.5.1 Location and description of the study area

Ulupalakua Ranch is a 6,470-ha farm located on the island of Maui (Figure 1) on the southwestern slopes of Haleakala (3055 masl) and runs approximately 2,300 brood cows of Brangus and Angus lineage. Much of the ranches' pasturelands, from an elevation of 600 to 1820 masl, are covered with the introduced African forage species *P. clandestinum* (kikuyu), which was introduced to the Hawaiian Islands in the 1800s. In a context of conservation, this species can be a deleterious weed that has a negative impact on native Hawaiian plant species (Daehler 2003). Kikuyu will produce seeds periodically but most quickly spreads through vegetative propagation of its stolons, spreading across vast areas in a dense mat and even secreting allelopathic compounds (Wilen and Holt 1996). This gives the plant a competitive advantage over native seedlings, which necessitates the establishment of *A. koa* by plantings. Nonetheless, this study sought to identify any potential scenarios in which reforestation and ranching could coexist within the same acreage and what the potential benefits of silvopastoral systems would be at this ranch.

Figure 1. Map of Maui, with site in Ulupalakua Ranch highlighted.
Source: QGIS 2013.

Ulupalakua Ranch (Figure 1) has engaged in various reforestation projects over the past four decades (Figure 2), some of which have utilized the reintegration of grazing ungulates and some of which have emphasized the full exclusion of ungulates to preserve rare endemic Hawaiian plant and animal species. Pu’u Makua (1600 masl) is one such example of a site on Ulupalakua Ranch lands that has been chosen as an environmental mitigation site and is currently being managed by a team of biologists and conservationists from the renewable energy company Auwahi Wind Energy to offset the potential environmental impacts of a windfarm located on leased lands on the lower southern slopes of the ranch on the native hoary bat ‘*ōpe‘ape‘a*. Although cattle and other ungulates are not allowed into this 53-ha (130-acre) area, it serves as a good location in which to observe the interaction between the native reforestation of *A. koa* and the remaining *P. clandestinum*.

One of the main objectives of the environmental mitigation site at Pu’u Makua is to increase areas of habitat and roosting for the endemic Hawaiian ōpe‘ape‘a hoary bat ōpe‘ape‘a *(Aeorestes semotus)*, believed to roost in the canopies of native tree species (Bonaccorso *et al*. 2016); these bats have been observed roosting in the vicinity. The upper elevations of the ranch are also home to the Hawaiian petrel or *‘ua’u (Pterodroma sandwichensis)*, Hawaiian goose or *nēnē (Branta sandwicensis)* and Blackburn´s sphinx moth *(Manduca blackburni)* (Auwahi Wind Energy 2019).

In addition to animal species, the slopes of leeward Haleakala are home to myriad endemic tree and plant species, many of which are threatened by habitat loss. The environmental and meteorological attributes of the site are well-suited for the outplanting of *A. koa*, *Metrosideros polymorpha*, *Pipturus albidus*, *Sophora crysophylla* and *Dodonaea viscosa*, among others. These are just some of the species being planted in certain sections of the Pu’u Makua mitigation site (Figure 2). A richness of species is conducive to conservation and prevents creation of a green desert as is often the case in a monotypic silvicultural environment (Bremer *et al.* 2010). The climate is considered mesic, with mean annual rainfall ranging from 30 to 40 inches, and a United States Department of Agriculture (USDA) plant hardiness zone of 11a. The soil type is uniform across the southwestern flank of the sampling site and is classified as an entisol (CTAHR 2014). Total rainfall for the nearest rain gauge at Kepuni Gulch measured 19.91 inches for 2019 (USGS 2019).

Figure 2. Aerial image of reforestation quadrants at Ulupalakua Ranch, Maui, Hawaii. Source: QGIS, 2013.

1.5.2 Relationships between **Acacia koa** *and pastures in Hawaii*

The upper elevations of Ulupalakua Ranch have a limited number of remnant *A. koa* trees and most stands have been planted within the past 30 years. Because cattle and other ungulates severely limit natural generation (Barrera and Kelly 1974), it has been necessary to construct 7-foot-tall exclosure fences to ensure the survival of young saplings that have been planted. There have been numerous studies done on natural regeneration of koa, particularly on the Big Island of Hawaii, which have proven that the exclusion of ungulates will spur koa reforestation (Baldwin and Fagerlund 1943). However, if trees are scarce, and the seed bank has been depleted, regeneration is unlikely (Baker *et al*.2009). A confounding factor on the island of Maui is that the deer species *Axis axis* can easily jump typical 5-foot cattle fencing, making natural koa regeneration even more difficult. However, once trees have been established for at least five years, it is possible to reintroduce grazing into the system (Grace 1995).

Research within the boundaries of Haleakala National Park found that koa trees had significantly higher survival and growth rates based upon the topographic relief of their location, with trees in (concave) basins having greater success (Scowcroft and Jeffrey 1999). There is also considerable evidence that the presence of *A. koa* has positive effects on soil properties, improving levels of carbon, phosphorus and nitrogen within 10 years of establishment (Baker *et al.* 2009). In terms of the effect of *A. koa* on the availability and quality of forage grasses, an extensive doctoral thesis on the Big Island found that low and medium density koa coverage provided increases in the forage quality of *P. clandestinum* (Grace 1995). We proposed that it would be likely that a similar study done on Maui would yield similar results and that differences in the phenology of size of phyllodes of Maui *A. koa* would make research particularly relevant on Maui.

Morphological variation of koa can be found on each island (Whitesell 1990). Given that ranching is the largest agricultural land use on Maui island, the incorporation of koa into kikuyu rangelands may have a significant impact on the island's productivity. *P. clandestinum* growing beneath koa at Pu'u Makua, under three densities of koa in sites 2, 3 and 24 can be seen in Figure 3.

Figure 3. Layout of reforestation quadrants at Ulupalakua Ranch, Maui, Hawaii. Courtesy of Auwahi Wind Energy.

2 Estimation of Carbon Sequestration and Leaf Area Index (LAI) in Three Densities of *Acacia koa*

2.1.Introduction

The variables measured in *A. koa* trees located at Pu'u Makua at Ulupalakua Ranch were total height (H), diameter at breast height (DBH), height to the first fork (commercial height–cH), leaf area index (LAI 4 ring), wood volume and carbon (the last two using allometric equations). To determine benefits in terms of wood and carbon in wood that would be present in the system. Samples were taken from three different densities of *A. koa* that had been planted at 3, 4 and 6 m apart (1,111 trees/ha, 625 trees/ha and 277 trees/ha, respectively). Trees found on the margin of each grove were not considered for measurement to eliminate the potential for inaccurate results due to the border effect.

2.2 Methodology

2.2.1 Measurements of **A. koa**

Measurements of *A. koa* were taken from a total of 21 trees from three different densities (3, 4 and 6 m apart*)* (7 trees from each density) at Pu'u Makua on Maui; these spacing could be converted to 1,111, 625 and 277 trees/ha. All of these stands were planted and were not from natural regeneration. Trees belonging to the cohort planted with spacing of 3 m were planted in approximately 2001, while the other cohorts of *A. koa* were planted in 2014 and 2015. DBH, H and cH were measured with forestry equipment to see the impact of various spacing on the growth of trees and, ultimately, on the LAI of the koa. Measurements were then input into allometric equations commonly used for *A. koa* (Baker *et al.* 2009) to get an idea of the volume of each tree and to estimate the amount of carbon sequestered within each tree. Due to heterogeneity in ages between plots 2 (20 years old), and plots 3 and 24 (6 years old), associated attributes of tree measurements with LAI rather than only densities were considered important.

2.2.2 Determination of LAI

To accurately estimate the amount of light and canopy cover projected by *A. koa*, we decided on a photo-based methodology to eliminate potential errors in light based upon the amount of sunlight at any given point. Given that intermittent cloud cover is prevalent at the site, it was necessary to focus on LAI rather than Mols light units. LAI can be defined as the maximum projected leaf area per unit ground surface area (Myneni *et al.* 1997). Koa is a phyllodial species that begins with true leaves and that eventually changes to having sickle-shaped phyllodes (Whitesell 1990). These phyllodes provide more efficient water use to koa. Given that the phyllode orientation of *A. koa* is vertical, rather than flat, significant sunlight can enter the system when the sun is at its zenith. During earlier or later hours of the day, more shade will be cast by the same canopy since these leaves (*phyllodes*) tend to block light from lower angles.

LAI was determined by taking multiple 180-degree hemispheric photos (Figure 4), with a fisheye lens in February of 2020 (rainy season). Photos were taken 1.5 m to the west-southwest of each tree sampled. Although koa may lose leaves during significant windstorms, it is not a deciduous species and does not lose and gain leaves to a significant degree. A total of *n=28* photos were taken (which corresponded to each location that forage samples were taken) and then uploaded into Gap Light Analyzer (Frazer et al. 1999), which is a software that can determine LAI based on the percentage of light blocked by foliage, branches and trunks of the forest canopy. Adjustments were made according the latitude, slope and elevation of the site to then determine LAI within the zenith angles of 0 to 60 degrees. *LAI* 4 Ring (0 to 60 degrees) was then utilized to observe potential correlations between density of *A. koa* canopy cover and attributes of the forage *P. clandestinum* (which can be seen as part of objective 2). Results from a photo (plot 2 tree #4) analyzed by this software are presented in Table 1 in the next section.

Figure 4. A 180-degree hemispheric photo, taken in Ulupalakua, Maui, Hawaii, with a fisheye lens. Source: Jon Spenser Photography.

2.3 Results and Discussion

2.3.1 Attributes of LAI

Results of hemispheric photo sampling for LAI under the canopy of *A. koa* produced high-resolution images that then yielded estimates for LAI once put into Gap Light Analyzer software (see image in Figure 4). Although this software provides percentage of canopy openness, LAI is the most appropriate measure of shade. These LAI results could then be cross-referenced with other attributes of koa as well as with attributes of kikuyu forage to make inferences on whether different densities of would in fact produce differences in tree growth or forage quality. An unpaired t-test comparing three densities of koa with full sun (no trees) was run, with the results shown in Table 1.

2.3.2 Average LAI for each group

Table 1. Average and standard deviation of sampling LAI from densities of koa of 3, 4 and 6 m.

GROUP	AVERAGE LAI	STANDARD DEVIATION
0	0.01	.02
3	0.69	0.15
4	0.88	0.13
6	0.34	0.15

Notes: Group 0 denotes full sun, or absence of trees. Group 3 denotes trees planted at 3 x 3 m distance. Group 4 denotes trees planted at 4 x 4 m distance. Group 6 denotes trees planted at 6 x 6 m distance. Group 3 trees were 20 -years old, while the others were 6 years old. These differences could not be corrected for LAI measurements.

Unpaired t-tests were utilized instead of paired t-tests or conventional ANOVA analysis to better understand differences between groups 0, 3, 4 and 6. The results of these tests are shown in Table 2.

Table 2. Unpaired t-test showing statistically significant differences of LAI between threedensities of *A. koa* and full sun. P-values less than .05 suggest a significant difference.

Clasific	Var.	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)/(2)	pHomVar	T	p-value	test
Density	LAI	{0}	{3}	7	7	0.01	0.69	-0.68	<0.0001	-11.9	<0.0001	Bilateral
Density	LAI	{0}	{4}	7	7	0.01	0.88	-0.87	0.0001	-17.7	<0.0001	Bilateral
Density	LAI	{0}	{6}	7	7	0.01	0.34	-0.33	<0.0001	-5.63	0.0013	Bilateral
Density	LAI	{3}	{4}	7	7	0.69	0.88	-0.19	0.7303	-2.59	0.0235	Bilateral
Density	LAI	{3}	{6}	7	7	0.69	0.34	0.35	0.9558	4.28	0.0011	Bilateral
Density	LAI	{4}	{6}	7	7	0.88	0.34	0.54	0.6893	7.13	<0.0001	Bilateral

Notes: Group 0 denotes full sun, or absence of trees. Group 3 denotes trees planted at 3 x 3 m distance. Group 4 denotes trees planted at 4 x4 m distance. Group 6 denotes trees planted at 6 x 6 m distance. Group 3 trees were 20 years old, while the others were 6 years old. These differences could not be corrected for LAI measurements.

The first three tests in Table 2 show that every group with planted trees has a larger LAI than the full sun one (Group 0), which would be obvious. The comparison between Groups 3 and 4 with Group 6 shows that LAI at this site is highest under a distance of 4 x 4 m.

The comparison between Groups 3 (high density) and 4 (mid tree density) shows that differences in LAI are not significant at the p>0.01 level, but significant at p>0.05. This result should also consider the difference in age between Groups 3 and 4, further reducing confidence in this comparison and making it highly necessary to suggest further research. A caveat and somewhat positive benefit to this differential in age is that we can have an idea of the LAI of trees planted at 3 m distance after 20 years.

An additional confounding factor is that the 4-m trees were planted in an area with less of a slope and within an area that could be defined as a swale. There is literature on this topic, in which investigators discovered that *A. koa* growing within concave topography grew more robustly than trees growing on a convex surface (Baker *et al.* 2009).

2.3.3 Statistical analysis of LAI in relation to A. koa *attributes*

Results from measurements taken of *A. koa* were input into the statistical software InfoStat (Di Rienzo *et al.* 2016 to analyze potential relationships between diameter at breast height and LAI. The sample size of each density was *n=7*, with a total of 21 trees measured from three different densities. Lineal regression, and coefficients of correlation, with p-value ≤ .05, were determined with the software to see whether statistically significant correlations existed. Any statistically significant relationships have been included, and any insignificant relationships have been excluded. LAI of *A. koa* in relation to density of planting can be seen in Figure 5. The p-value of this relationship is .0012, which represents a strong distinction in differences of LAI among various densities of koa (Table 3).

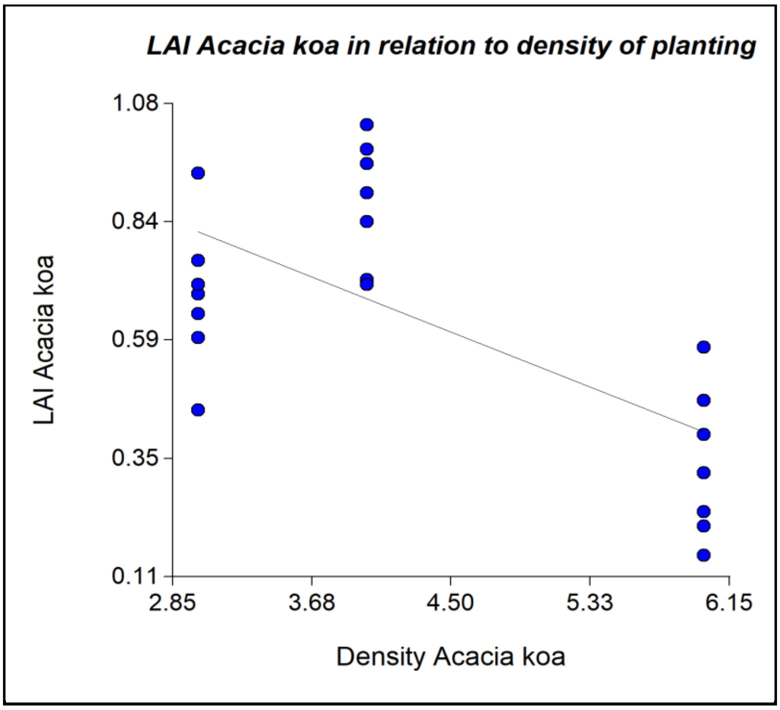

Figure 5. LAI of *A. koa* in relation to density distance between *Acacia koa* trees (3, 4, 6 m distance). Trees planted at a 3 x 3m distance (Group 3) are 20 years old, while the others are only 6 years old.

Table 3. LAI of *A. koa* in relation to density (3, 4, 6 m distance).

Lineal regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
LAI Acacia koa	21	0.43	0.4	0.05	-2.78	0.36

Coefficients of regression						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	1.23	0.16	0.89	1.57	7.57	<0.0001
Density Acacia koa	-0.14	0.04	-0.21	-0.06	-3.82	0.0012

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	0.62	1	0.62	14.57	0.0012
Density A. koa	0.62	1	0.62	14.57	0.0012
Error	0.81	19	0.04		
Total	1.43	20			

**P-values less than 0.05 suggest a significant difference.*

Results showed that there were statistically significant differences between the LAI of various densities of koa (Table 1), with koa planted at a distance of 6 m obviously having the lowest mean LAI (0.34), with a standard deviation of 0.15. Interestingly, koa planted at a distance of 4 m had a higher mean LAI (0.88) than trees planted at a distance of 3 m (0.69), despite the fact that trees planted at 3 m were planted more than 10 years earlier. This could be attributable to the fact that the 4 m trees were planted in an area with less of a slope and within an area that could be defined as a swale. There is in fact literature on this topic, in which investigators discovered that *A. koa* growing within concave topography grew more robustly than trees growing on a convex surface (Baker *et al.* 2009). LAI of koa in relationship to DBH can be seen in Figure 6. Although the p-value of this relationship is less than .05, a value of .045 does not necessarily suggest a strong relationship (Table 4).

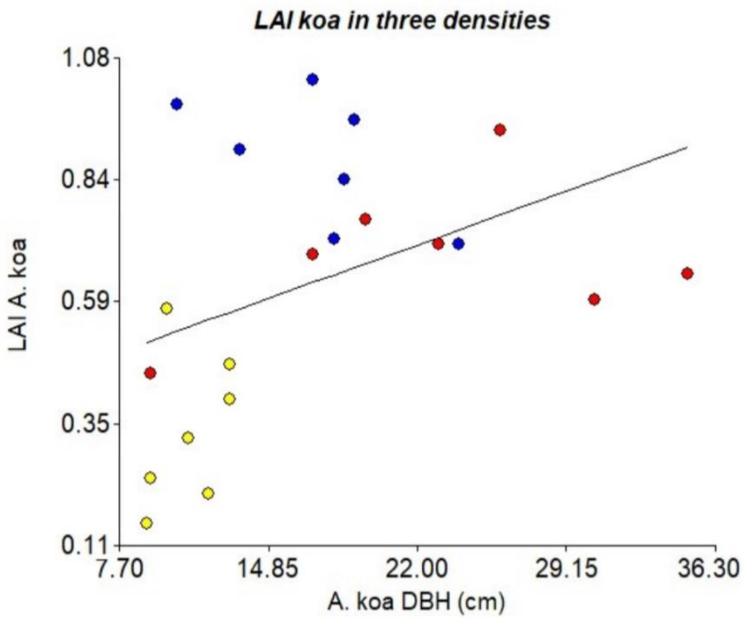

Figure 6. LAI of *A. koa* in various densities of *A. koa* trees (3, 4, 6 m distance), with DBH of *A. koa* in the x-axis. Trees planted at a 3 x 3 m distance (yellow) are 20 years old, while trees planted at 4 x 4 m (blue) and 6 x 6 m (red) are only 6 years old.

Table 4. Statistics: LAI of *A. koa* in relation to DBH (statistics).

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
LAI Acacia koa	21	0.19	0.15	0.08	4.63	7.77

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.38	0.13	0.11	0.65	2.9	0.0091
Acacia koa DBH (cm)	4.90E-03	2.30E-03	1.10E-04	0.01	2.14	0.0454

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	0.28	1	0.28	4.59	0.0454
Acacia koa DBH (cm)	0.28	1	0.28	4.59	0.0454
Error	1.15	19	0.06		
Total	1.43	20			

coefficients of correlation				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
LAI Acacia koa	Acacia koa DBH (cm)	21	0.44	0.045

**P values less than 0.05 suggest a significant difference.*

2.3.4 Attributes of tree dimensions and potential for carbon sequestration

Current stock of koa on Maui is not indicative of the size this species can attain. The largest koa tree on record had a height of 43 m (140 ft), DBH of 363 cm (143 in) and a crown spread of 45 m (148 ft) (Whitesell 1990). Within the past two centuries, cattle, forest fires and harvesting have decimated koa, leaving much smaller sizes, if any trees at all.

Koa growing at Pu'u Makua is at a high enough elevation to avoid high concentrations of the endemic koa seedworm (*Cryptophlebia illepida* Butler) and the invasive introduced black twig borer *(Xylosandrus compactus)*, as well as the pathogenic wilt fungus *Fusarium oxysporum* (Baker *et al.* 2009). The trees at this elevation can also grow robustly since they are able to capture mist from clouds. The soil type is a volcanic andisol/entisol, which is conducive to healthy growth. Once planted, the trees received no prunings or thinnings, which allows us to assess any relationships between tree spacing (or LAI) and tree attributes such as overall height, DBH and height to the first fork. It is worth noting that plot 3 (6 m spacing) was planted in the spring of 2015 and plot 24 (4 m spacing) was planted during the fall of 2014, while plot 2 was planted in the early 2000s. It is also important to note that plot 3 was planted with 2-inch dibble tube koas (1–2 ft.), while plot 24 was planted with 2-gallon koa (5–6 ft koa), which further leads us to avoid making suggestions based on comparisons. As recently as 2017, herbicide treatments were utilized on kikuyu for the establishment of koa (personal communication with site biologist George Akau, November 2019). Although the most recent grass-specific herbicide applications occurred in 2017, this could still be a confounding factor in forage analysis found in section 3. However, it is likely that three years without the application of Fusilade herbicide is a long enough time period for all kikuyu within plots to have recovered. Periodic spot applications of glyphosate have been used to discourage weeds, notably Himalayan blackberry (*Rubus discolor*; syn: *Rubus armeniacus*). Without homogeneity in planting age, we cannot draw assumptions on whether a spacing of 3 m is superior to 4 m or 6 m as far as timber is concerned. However, we can form a general idea of the dimensions, woody biomass and carbon sequestration of trees within each of the densities. General allometric equations for koa are presented in Table 5.

Results and descriptive statistics of DBH, height to first fork, height, LAI, whole tree biomass and carbon stock estimate can be found in Tables 6, 7, 8, 9, 10, 28, 29, 30 and A.1. See Figure 7 for a carbon-stock estimate per tree. An unpaired t-test showed statistically significant differences of carbon between three densities of *A. koa* and full sun (Table 9). It is important to note that trees were not planted during the same year, and this lack of homogeneity necessitates further studies. A carbon stock estimate of trees in various densities can be seen in Figure 7 and Table 7. Allometric equations used in our carbon estimate can be found in Table 5. It was determined by means of allometric equations that the amounts of carbon sequestered in each density would be approximately 126.03 tons/ha for a 20-year-old stand of koa planted in a density of 1,111 trees/ha, approximately 9.03 tons/ha for a 6-year-old stand of koa planted in a density of 625 trees/ha, and approximately 13.42 tons/ha for a 5-year-old stand of koa planted in a density of 277 trees/ha.

Table 5. Established allometric equations for *A. koa* in the Hawaiian Islands established by (Conrad 2005) and (Fownes and Grace 1995).

Tree component and site ID *Whole tree biomass:*	**Elevation** *Meters*	**Age** *Years*	**DBH range** *Centimeters*	**Equation form**[a]	**a**[b]	**b**	**R**^{2}
M-06 [d]	1070	6 to 8	5 to 26	$BA=aDBH^b$	0.057	2.578	0.99
Wood biomass:							
H-05/H-12	1400-1700	8 to 17	2 to 30	$BW=aBD^b$	0.067	2.418	NA

Table 6. Attributes of various densities of *A. koa*.

ITEM	Description	DBH (cm)	Height to first fork (cm)	Height (m)	LAI	Carbon estimate(kg)
1	*Acacia koa* 3 m #1	35	58	8.5	0.65	272.55
2	*Acacia koa* 3 m #2	17	86	8.8	0.69	42.355
3	*Acacia koa* 3 m #3	30.5	137	9.1	0.6	191.145
4	*Acacia koa* 3 m #4	9.2	71	4.2	0.45	8.695
5	*Acacia koa* 3 m #5	23	86	8.2	0.71	92.335
6	*Acacia koa* 3 m #6	19.5	274	7.9	0.76	60.33
7	*Acacia koa* 3 m #7	26	124	7.3	0.94	126.66
8	*Acacia koa* 6 m #1	9.2	119	3	0.24	8.695
9	*Acacia koa* 6 m #2	13	124	4.4	0.4	21.21
10	*Acacia koa* 6 m #3	9	144	3.3	0.15	8.22
11	*Acacia koa* 6 m #4	12	121	3.6	0.21	17.255
12	*Acacia koa* 6 m #5	13	149	4.26	0.47	21.21
13	*Acacia koa* 6 m #6	10	86	3.65	0.58	10.785
14	*Acacia koa* 6 m #7	11	144	3.3	0.32	13.785
15	*Acacia koa* 4 m #1	17	218	5.2	1.04	42.355
16	*Acacia koa* 4 m #2	19	162	5.5	0.96	56.425
17	*Acacia koa* 4 m #3	18	127	5.3	0.72	49.08
18	*Acacia koa* 4 m #4	10.5	132	4.1	0.99	12.23
19	*Acacia koa* 4 m #5	18.5	167	5.6	0.84	52.675
20	*Acacia koa* 4 m #6	13.5	157	4.4	0.9	23.38
21	*Acacia koa* 4 m #7	24	208	6.2	0.71	103.045

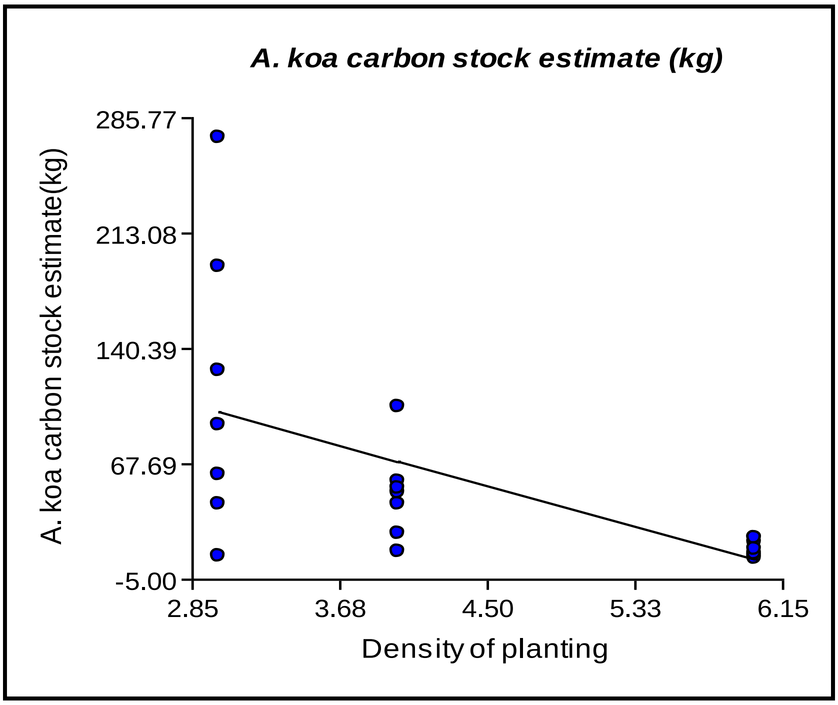

Figure 7. Carbon sequestration estimate (kg per tree) of individuals of *A. koa* in relation to density (3, 4, 6 m distance) on a per tree basis. The x-axis represents the spacing in meters between trees planted. The y-axis represents the approximate amount of carbon sequestration (in kg/tree) of individuals sampled in three different densities.

Table 7. Carbon sequestration estimate (kg) of *A. koa* in relation to density (3, 4, 6 m distance).

Lineal regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
A. koa carbon stock estimate	21	0.34	0.3	3910.72	232.95	236.09

Coefficients of regression						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	191.95	44.6	98.6	285.29	4.3	0.0004
Density of planting	-30.73	9.89	-51.43	-10.02	-3.11	0.0058

ANOVA					
F.V.	SC	gl	CM	F	p-value
Model	30839.4	1	30839.4	9.65	0.0058
Density A. koa	30839.4	1	30839.4	9.65	0.0058
Error	60714.16	19	3195.48		
Total	91553.56	20			

**P-values less than 0.05 suggest a significant difference.*

Results in Table 7 show the relationship between density of planting and estimates of carbon sequestration (in kg). While there were no allometric equations for this exact site, the most appropriate equation for whole tree biomass was at a similar elevation on the island of Maui (Baker *et al.* 2009), thus yielding an estimate of aboveground and belowground biomass. Overall biomass was used to estimate carbon stock in kilograms. It is important to note that trees from densities of 4 x 4 m and 6 x 6m were planted 6 years ago, and that trees planted in a density of 3 x 3 m were planted 20 years ago. While this limits homogeneity of samples, and the ability to make comparisons (and planting suggestions), it does provide a general view of carbon sequestration among three densities and two ages of koa. The average carbon stock estimates and standard deviation of koa planted at 4 and 6 m apart are presented in Table 8.

Table 8. Average carbon and standard deviation of sampling for carbon stock estimate from densities of koa of 4 and 6 m.

GROUP	AVERAGE CARBON STOCK (kg/tree)	STANDARD DEVIATION
4	48.46	28.98
6	15.18	4.98

A comparison (via t-test) in carbon stock estimate between the means of koa planted at a distance of 4 m versus 6 m yields a statistically significant difference with a p-value of .0226, with trees at a 4 m density yielding a significantly higher volume (as seen in Table 9). The standard deviation of carbon sequestration of trees from a density of 4 m is a higher value of 28.98, versus a standard deviation of 4.98 for trees planted in a density of 6 m (Table 9)). Groups 4 and 6 were planted within one year of each other (albeit with slightly difference sapling sizes). This is suggestive of hierarchical dominance taking place in a closer density of koa.

Table 9. Unpaired t-test showing differences of carbon between three densities of *A. koa*.

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	M(1)-M(2)	LI(95)	LS(95)	pHomVar	T	p-value	test
Density	Carbon est. (kg.	{3}	{4}	7	7	113.44	48.46	64.98	-21.3	151.2	0.0128	1.8	0.118	Bilateral
Density	Carbon est. (kg.	{3}	{6}	7	7	113.44	14.45	98.99	13.72	184.3	<0.0001	2.8	0.0295	Bilateral
Density	Carbon est. (kg.	{4}	{6}	7	7	48.46	14.45	34	6.71	61.3	0.0008	3.1	0.0226	Bilateral

***P-values less than 0.05 suggest a significant difference.**

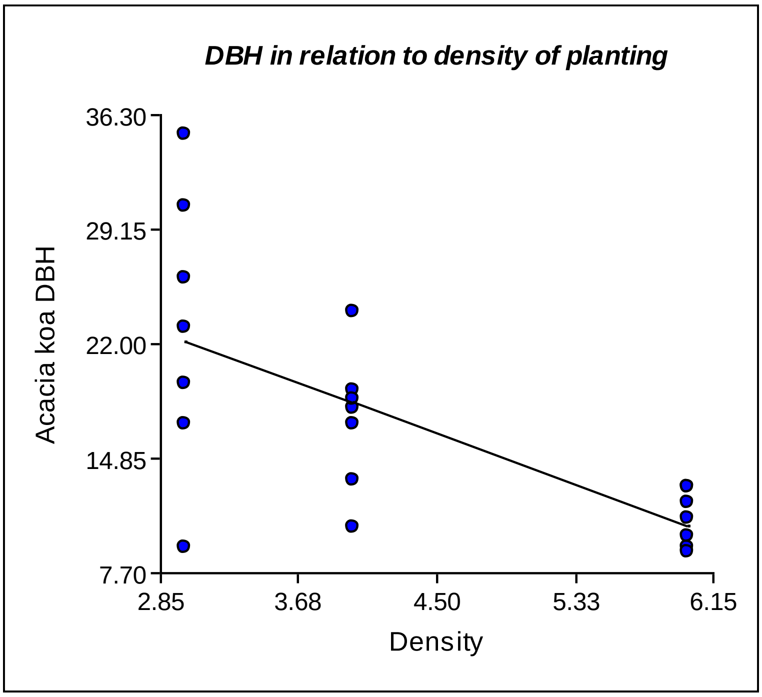

Figure 8. DBH of *A. koa* in relation to density (3, 4, 6 m). Higher densities of *A. koa* planted tended to yield a reduced DBH. Note that trees with a spacing of 4 and 6 m were planted within one year of each other, while trees planted at 3 m were planted approximately 10 years prior. This provides a window into potential growth patterns but not necessarily a homogenous comparison.

Table 10. Statistics: DBH of *A. koa* in relation to density (3, 4, 6 m).

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Acacia koa DBH	21	0.45	0.42	37.71	135.6	138.73

Regression coefficients	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	33.64	4.39	24.45	42.83	7.66	<0.0001
Density	-3.83	0.97	-5.87	-1.79	-3.93	0.0009

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo	479.08	1	479.08	15.46	0.0009
Density	479.08	1	479.08	15.46	0.0009
Error	588.81	19	30.99		
Total	1067.89	20			

**P-values less than 0.05 suggest a significant difference.*

To better understand DBH of *A. koa* trees at various densities and ages, an analysis of variance test was performed. While there were significant differences in DBH between various densities, there were too many heterogeneous differences in stand age and slope of topography to make inferences on the best density of planting in regard to DBH (Figure 8). Table 10 and statistical analysis presented indicate that there are significant differences in the mean and distribution of each density. However, we cannot make suggestions as to which density yields the highest DBH due to inconsistencies in conditions and a relatively small sample size *(n=7)*. We can, however, see a general trend in hierarchical dominance among older trees and trees planted closer together due to competition within the stand. Trees planted farther apart, at a distance of 6 m, tended to have less variance in DBH than trees planted at a distance of 3 and 4 m.

2.4 Conclusions

There are many ecosystem services of trees in a ranching landscape, including but not limited to water retention, aquifer recharge and increased biodiversity. This study focused on the potential for carbon sequestration within three densities of koa. Sampling and subsequent analysis demonstrated that there are notable trends associated with various densities of koa. Although stands were not planted in the same year, a spacing of 4 m tended to yield higher DBH values than trees planted 6 m apart, with a p-value under .05. Overall biomass as a result of DBH and height input into established allometric equations yielded estimates of carbon per hectare that can be utilized to plan for future projects.

2.4.1 Benefits of koa for carbon sequestration

Carbon sequestration by reforestation of trees in a ranching landscape is considered one of the strategies to mitigate the effects of climate change (IPCC 2003). Several tree species in the *Acacia* group have been used in silvopastoral systems, including *A. mangium*, and *A. decurrens* (Giraldo 1995). There have been various studies on carbon sequestration in *A. koa* on the Big Island of Hawaii, which showed that there is potential for the sale of carbon credits and other incentives for the conservation of koa on private lands (Goldstein *et al.* 2006). This research examined carbon stock estimates for n=21 locations under three different densities of *A. koa* (3, 4 and 6 m apart). Based upon these results, it appears that a density of 3 m has the highest mean amount of carbon sequestration per tree (113.44 kg). However, given that we did not have homogeneity in age between all densities, this does not give us the most accurate answer regarding which density is preferable for carbon sequestration. That leaves us with the ability to compare *A. koa* densities of 4 and 6 m, since they were planted the same year (2015). It appears that a density of koa planted at 4 m is optimal for carbon sequestration at this site, given that the mean carbon stock of trees planted at this distance is 48.46 kg while the mean carbon stock of trees planted at 6 m is 14.45 kg. A caveat is that the 4-m sampling site was on flatter terrain (10 degrees) as compared to a slope of roughly 20 degrees where 6 m koa was planted. It is noteworthy that the standard deviation of estimated biomass and carbon stock in older trees (planted at a density of 3 m) increased, suggesting that competitive hierarchy may be playing a role in this system. This phenomenon is well-documented in *A. koa* (Conrad *et al.* 1990; Whitesell 1990). We suggest that future research look further into this subject, with a larger sampling size.

In our study, height of koa in relation to density tended to increase with a closer density, with the standard deviation increasing with age, suggesting that trees will establish hierarchal dominance. It is notable that *P. clandestinum* possesses allelopathic properties (Marais 2001), which may affect the performance of young koa. It is advisable to follow a planting protocol that protects *A. koa* until it can adequately compete with kikuyu. Foresters establishing *A. koa* in kikuyu-dominated grasslands commonly use glyphosate and other herbicides, which may not be advisable given that kikuyu may be able to adapt and develop glyphosate tolerance (Storrie *et al*. 2012). Although there is ample anecdotal evidence on the establishment of koa in kikuyu grasslands, more studies are needed to identify such strategies.

3 Forage Analysis of *Pennisetum clandestinum* beneath Three Densities of *Acacia koa* Compared with Full Sun

3.1 Introduction

The relationship between tree cover and forage availability and quality can be complex and create certain benefits while having certain trade-offs. The goal of our second objective was to evaluate the effect of shade cover (and nutrient cycling) of *A. koa* on the availability and quality of the forage *P. clandestinum* in three densities of koa (Villanueva *et al.* 2008), as compared with full sun at Ulupalakua Ranch on the island of Maui, during dry season (July 2019) and wet season (March 2020) (Figure 9).

3.2 Methodology

To adequately understand this interaction between *P. clandestinum* and *A. koa* throughout the whole year, *n=28* samples of kikuyu were taken in dry season (July 2019), 21 of which were taken from beneath three densities of *A. koa,* and 7 in full sun. Measurements of *A. koa* were taken from underneath a total of 21 trees from three different densities. These densities were trees planted at spacings of 3, 4 and 6 m apart (7 trees from each density) at Pu'u Makua on Maui. These spacings would represent (1,111 trees/ha, 625 trees/ha, 277 trees/ha). In trees per square meter, these spacings would represent .11 trees/m^2 , .0625trees/m^2, .027 trees/m^2. There was relative homogeneity of soil type (entisol), and orientation of slope (west-southwest).

This same process of taking *n=28* samples was performed in wet season (March 2019). (Zapata *et al.* 2013). Pu'u Makua is technically an environmental mitigation site and does not experience grazing from cattle herds or wild ungulates of any sort. Therefore, to accurately estimate availability and quality of forage, we decided to employ a methodology in which we simulated grazing by cutting the kikuyu to a height of approximately 4 inches in a quadrant measuring 50 x 50 cm at each sampling site 45 days prior to our actual forage samples. We did not sample kikuyu growing beneath trees found on the margin of each grove to eliminate the potential for inaccurate results due to the border effect.

We returned to the site 45 days after this simulated grazing to take kikuyu samples. Forage samples were taken approximately 1.5 m to the west-southwest of each tree. Given that the general slope of each plot of koa faced the same direction, and that the winds blow predominately out of the east-northeast in Hawaii (despite the fact that Ulupalakua is on the lee of Haleakala and often experiences convective winds), which increases leaf litter to the west-southwest, this method allowed the greatest degree of control over sampling conditions. There were small variations in hillslope from location to location but the general slope of the site (with the exception of plot 24) was 25 degrees. It is noteworthy that plot 24 grows within a concave swale, which may have produced different results than convex areas. Samples were cut to a height of approximately 4 inches using shears as well as a 50 x 50 cm quadrant to standardize the area of each sample taken. Samples were then sent to the Agricultural Diagnostics Laboratory at the University of Hawaii at Manoa, where forage analysis was done to determine the attributes of kikuyu under *A. koa,* as well as under full sun. Forage attributes measured included dry matter, ash, crude protein, neutral detergent fiber

(NDF), acid detergent fiber (ADF), lignin, cellulose and micronutrients (B, Ca, Cu, Fe, Mg, Mn, P, K, Na, Zn).

Statistical analysis was done with the software InfoStat Version 2016 (Di Rienzo *et al.* 2016) to determine whether there is a significant difference in forage quality beneath shade and in full sun (with $p \leq 0.05$). The measurement of LAI conducted for objective 1 was utilized to draw comparisons between the performance of kikuyu under different conditions (Esquivel 2007). Results of hemispheric photo sampling for LAI under the canopy of *A. koa* produced high-resolution images that then yielded estimates for LAI once input into Gap Light Analyzer software. This allowed for more insights and analysis of the relationship between the LAI of various densities of *A. koa* and forage attributes of *P. clandestinum.*

3.2.1 Dry season forage statistical analysis

To measure the forage quality and quantity of kikuyu *(Pennisetum clandestinum)* during the dry season, a total of *n=28* samples were taken. *n=7* samples were taken from three different densities of *A. koa* groves, as well as from full sun. All areas were occupied exclusively by kikuyu grass, as confirmed by mitigation site transects (which showed coverage exceeding 95%). Dry season forage analysis results were produced by the University of Hawaii Agricultural Diagnostic Service Center measuring a total of 19 different attributes (phosphorus, potassium, calcium, magnesium, sodium, iron, manganese, zinc, copper, boron, dry matter, ash, crude protein, fat, neutral detergent fiber, acid detergent fiber, lignin, cellulose and weight.

Figure 9. Sampling site for kikuyu *(P. clandestinum)* growing beneath *A. koa* in Ulupalakua, Maui, Hawaii. Source: Personal photo.

3.3 Results and Discussion

Forage analysis results from the Agricultural Diagnostics Service Center at the University of Hawaii at Manoa were input into Excel spreadsheets (for the dry season and the wet season) and then input into InfoStat statistical software to draw inferences about meaningful relationships. Columns included measurements of phosphorus, potassium, calcium, magnesium, sodium, iron manganese, zinc, copper, boron, dry matter, ash, crude protein, fat, neutral detergent fiber, acid detergent fiber, lignin, cellulose and weight. Results within each season were horizontally categorized into koa 3 m, koa 4 m, koa 6 m and full sun. Forage analysis results can be seen in Table 11.

3.3.1 Dry season forage analysis results

Table 11. Dry season forage analysis of *P. clandestinum* growing at Ulupalakua Ranch, Maui, Hawaii.

		%						ug/g			D.M%	Ash%	CP%	FAT%	NDF%	ADF%	Lignin%	Cellu%	weight (g)
Acacia koa	**P**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	
koa 3m #1	0.30	3.39	0.35	0.34	0.05	196	19	125	4	6	79.32	7.84	20.19	1.97	56.40	25.43	7.79	17.64	171.00
koa 3m #2	0.24	2.97	0.32	0.28	0.03	190	17	81	2	8	66.69	6.66	18.23	1.82	58.84	27.87	7.60	20.26	193.00
koa 3m #3	0.24	2.85	0.29	0.27	0.03	165	12	44	2	6	74.09	7.30	18.83	1.86	58.93	26.12	6.57	19.55	219.00
koa 3m #4	0.21	2.09	0.23	0.21	0.04	151	14	48	1	6	74.53	6.20	15.73	1.70	62.64	29.37	9.31	20.06	239.00
koa 3m #5	0.26	3.30	0.22	0.21	0.03	146	11	41	3	5	65.77	7.47	17.98	2.16	60.14	28.80	6.24	22.56	267.00
koa 3m #6	0.17	2.09	0.25	0.20	0.04	147	11	50	1	5	84.88	6.23	12.53	1.35	63.23	30.05	10.47	19.58	188.00
koa 3m #7	0.17	1.99	0.27	0.23	0.04	173	13	89	1	5	72.88	6.14	12.80	1.30	63.00	28.93	7.75	21.17	219.00
koa 6m #1	0.26	2.48	0.21	0.24	0.03	159	16	104	3	4	79.00	7.28	10.75	1.28	64.42	31.26	9.65	21.61	164.00
koa 6m #2	0.26	2.70	0.22	0.24	0.03	167	16	47	2	4	68.74	6.90	11.95	3.09	62.65	30.51	6.30	24.21	156.00
koa 6m #3	0.23	2.46	0.19	0.19	0.03	157	15	48	1	4	73.52	7.17	9.03	2.99	65.81	32.07	7.40	24.67	234.00
koa 6m #4	0.24	2.72	0.19	0.21	0.03	186	17	139	1	4	63.87	5.74	10.70	3.07	65.79	30.58	6.35	24.23	190.00
koa 6m #5	0.24	2.46	0.15	0.20	0.03	132	12	56	1	4	63.31	5.64	11.36	3.32	63.53	30.50	9.23	21.27	248.00
koa 6m #6	0.24	2.25	0.25	0.22	0.04	183	17	45	1	4	88.52	7.74	9.88	2.83	65.40	32.40	8.80	23.61	185.00
koa 6m #7	0.30	2.68	0.26	0.25	0.03	183	21	62	1	4	87.92	7.85	10.38	3.12	65.09	30.61	7.20	23.41	149.00
koa 4m #1	0.26	2.26	0.17	0.19	0.03	120	15	106	1	4	71.87	5.73	13.12	3.09	63.35	29.54	6.36	23.19	171.00
koa 4m #2	0.36	2.57	0.17	0.20	0.02	122	20	158	3	4	69.14	6.08	16.24	3.53	61.51	27.70	5.54	22.16	167.00
koa 4m #3	0.30	2.95	0.19	0.21	0.02	127	18	65	4	4	77.42	7.33	16.75	3.34	61.17	28.22	5.14	23.08	181.00
koa 4m #4	0.31	2.56	0.20	0.20	0.02	126	20	71	2	4	84.31	7.67	14.02	3.62	63.23	29.58	7.87	21.70	150.00
koa 4m #5	0.29	2.33	0.17	0.19	0.02	144	19	147	2	4	56.40	4.97	14.09	3.28	60.73	29.64	6.64	22.99	142.00
koa 4m #6	0.32	2.64	0.17	0.17	0.02	121	15	65	1	4	62.81	5.79	13.50	3.52	62.15	28.17	3.51	24.66	273.00
koa 4m #7	0.24	1.91	0.19	0.19	0.02	127	16	60	1	4	85.53	7.47	12.27	2.87	62.70	28.73	5.53	23.20	273.00
Full Sun	0.17	0.95	0.18	0.18	0.01	129	23	60	1	3	77.65	4.45	5.98	1.74	69.98	38.21	12.84	25.37	264.00
Full Sun	0.16	0.72	0.21	0.19	0.01	167	14	63	1	3	78.23	5.00	4.43	1.93	68.77	37.16	11.55	25.62	165.00
Full Sun	0.16	1.03	0.23	0.17	0.01	116	21	94	1	4	88.70	4.78	4.67	2.14	68.09	36.63	8.96	27.67	131.00
Full Sun	0.17	1.17	0.23	0.18	0.01	140	12	32	1	3	58.21	3.13	5.66	2.07	66.11	34.24	6.72	27.52	170.00
Full Sun	0.27	1.81	0.19	0.20	0.02	99	14	51	2	3	85.77	5.70	10.00	2.86	66.59	34.72	8.44	26.28	119.00
Full Sun	0.17	1.32	0.20	0.16	0.01	125	28	177	1	3	71.44	4.60	5.14	1.73	70.12	37.34	9.19	28.16	174.00
Full Sun	0.18	0.96	0.19	0.16	0.01	206	28	86	1	3	69.77	3.88	5.25	2.03	69.31	37.88	9.92	27.97	216.00

For dry season forage analysis, each one of these 19 attributes of forage analysis from each sampling site was paired with the LAI of the canopy above that particular site, yielding a correlative graph and p-value that suggested whether LAI (and thus *A. koa*) had a positive or negative influence on the quality and quantity of forage. Results were input into the statistical software InfoStat (Di Rienzo *et al.* 2016) to analyze potential relationships. Lineal regression, and coefficients of correlation, with p-value ≤ .05 were determined with the software to see whether statistically significant correlations existed. Pearson's correlation coefficient was also used to measure the statistical relationship between these variables, by method of covariance (Table 10). Graph and table representations of attributes of kikuyu forage analysis in relation to LAI of *A. koa* from the dry season can be found in the appendix (Tables A.5 through A.15). There were marked increases in quality, particularly during dry season, which may be attributable to increased shade, water retention and nutrient cycling.

The following attributes of kikuyu were determined to be correlated with the LAI of *A. koa* (via Pearson's correlation) with a p-value ≤ .05: phosphorus, potassium, sodium, boron, ash, crude protein, neutral detergent fiber, acid detergent fiber, lignin and cellulose. The following attributes of kikuyu were determined *not* to be correlated with the LAI of *A. koa* (via Pearson's correlation) with a p-value ≤ .05: calcium, magnesium, iron, manganese, zinc, copper, fat and green weight. During dry season, there was no significant correlation between yield of kikuyu and LAI (p-value = .446), and no significant relationship between dry matter (%) and LAI either (p-value= .5992). There were, however, significant connections between the LAI of *A. koa* and crude protein, ADF (acid detergent fiber), NDF (neutral detergent fiber), lignin and cellulose. All of these attributes had a p-value of .0001 and can be found in the appendix (tables A.8, A.9, A.10, A.11, A.12).

Unpaired t-tests showed that there were significant differences in yield, CP, NDF, ADF, lignin and cellulose of *P. clandestinum* growing beneath koa versus full sun (no trees). These t-tests can be found in Tables 13, 14, 15, 16, 17 and 18. It is noteworthy that while a density of 3 m of *A. koa* produced a higher yield/availability of kikuyu in grams per square meter, there were not large differences between forage availability during the dry season. It is noteworthy that the notable differences in quality in regards to crude protein (Table 14), NDF (Table 15), ADF (Table 16), lignin (Table 17) and cellulose (Table 18) highlight overall superiority of forage growing beneath koa, at least during the dry season.

Table 12. Pearson correlation analysis of relationships between kikuyu forage attributes LAI of koa in dry season. P-values less than .05 suggest a relationship between the two variables. P-values exceeding .05 suggest that no statistically significant relationships between the two variables exist.

Pearson correlation *(dry season)*

Variable(1)	Variable(2)	n	Pearson	p-value
Phosphorus % Kikuyu	LAI Acacia koa	28	0.57	0.0015
Potassium % Kikuyu	LAI Acacia koa	28	0.62	0.0004
Calcium % Kikuyu	LAI Acacia koa	28	0.08	0.6823
Magnesium % Kikuyu	LAI Acacia koa	28	0.26	0.176
Na % Kikuyu	LAI Acacia koa	28	0.47	0.0125
Iron (u/ug) Kikuyu	LAI Acacia koa	28	-0.1	0.6135
Manganese ug/g Kikuyu	LAI Acacia koa	28	-0.29	0.1287
Zinc ug/g Kikuyu	LAI Acacia koa	28	0.1	0.6101
Copper ug/g Kikuyu	LAI Acacia koa	28	0.31	0.1114
Boron ug/g Kikuyu	LAI Acacia koa	28	0.47	0.0119
D.M.% Kikuyu	LAI Acacia koa	28	-0.1	0.5992
Ash % Kikuyu	LAI Acacia koa	28	0.49	0.0082
Crude Protein % Kikuyu	LAI Acacia koa	28	**0.76**	0.0001
Fat % Kikuyu	LAI Acacia koa	28	0.33	0.0883
NDF % Kikuyu	LAI Acacia koa	28	**-0.75**	0.0001
ADF % Kikuyu	LAI Acacia koa	28	**-0.81**	0.0001
Lignin % Kikuyu	LAI Acacia koa	28	**-0.54**	0.0027
Cellulose % Kikuyu	LAI Acacia koa	28	**-0.66**	0.0001
Green weight (g) Kikuyu	LAI Acacia koa	28	0.15	0.4446

Table 13. Unpaired t-test density and yield (g/m2) (dry season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Media(1)	Media(2)	Media(1)-(2)	pHomVar	T	p-value	Test
Density	Yield g/m2	{0}	{3}	7	7	708	854.86	-146.86	0.3366	-1.63	0.1283	Bilateral
Density	Yield g/m2	{0}	{4}	7	7	708	775.43	-67.43	0.7893	-0.6	0.5606	Bilateral
Density	Yield g/m2	{0}	{6}	7	7	708	757.71	-49.71	0.548	-0.52	0.6097	Bilateral
Density	Yield g/m2	{3}	{4}	7	7	854.86	775.43	79.43	0.2243	0.81	0.4315	Bilateral
Density	Yield g/m2	{3}	{6}	7	7	854.86	757.71	97.14	0.712	1.27	0.2271	Bilateral
Density	Yield g/m2	{4}	{6}	7	7	775.43	757.71	17.71	0.3886	0.17	0.8652	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 14. Unpaired t-test density and CP (%) (dry season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	CP%	{0}	{3}	7	7	5.88	16.61	-10.74	0.2864	-8	<0.0001	Bilateral
Density	CP%	{0}	{4}	7	7	5.88	14.28	-8.41	0.7293	-8.89	<0.0001	Bilateral
Density	CP%	{0}	{6}	7	7	5.88	10.58	-4.7	0.1193	-5.86	0.0001	Bilateral
Density	CP%	{3}	{4}	7	7	16.61	14.28	2.33	0.1641	1.8	0.0969	Bilateral
Density	CP%	{3}	{6}	7	7	16.61	10.58	6.03	0.0133	5.06	0.0015	Bilateral
Density	CP%	{4}	{6}	7	7	14.28	10.58	3.71	0.2155	5.18	0.0002	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 15. Unpaired t-test density and NDF (%) (dry season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	NDF%	{0}	{3}	7	7	68.42	60.45	7.97	0.2539	6.94	<0.0001	Bilateral
Density	NDF%	{0}	{4}	7	7	68.42	62.12	6.3	0.313	8.85	<0.0001	Bilateral
Density	NDF%	{0}	{6}	7	7	68.42	64.67	3.75	0.5235	4.99	0.0003	Bilateral
Density	NDF%	{3}	{4}	7	7	60.45	62.12	-1.67	0.0395	-1.58	0.1529	Bilateral
Density	NDF%	{3}	{6}	7	7	60.45	64.67	-4.22	0.0838	-3.9	0.0021	Bilateral
Density	NDF%	{4}	{6}	7	7	62.12	64.67	-2.55	0.703	-4.27	0.0011	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 16. Unpaired t-test density and ADF (%) (dry season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	ADF%	{0}	{3}	7	7	36.6	28.08	8.52	0.796	9.77	<0.0001	Bilateral
Density	ADF%	{0}	{4}	7	7	36.6	28.8	7.8	0.1344	11.91	<0.0001	Bilateral
Density	ADF%	{0}	{6}	7	7	36.6	31.13	5.46	0.1386	8.33	<0.0001	Bilateral
Density	ADF%	{3}	{4}	7	7	28.08	28.8	-0.72	0.0838	-1	0.3369	Bilateral
Density	ADF%	{3}	{6}	7	7	28.08	31.13	-3.05	0.0866	-4.26	0.0011	Bilateral
Density	ADF%	{4}	{6}	7	7	28.8	31.13	-2.34	0.9859	-5.46	0.0001	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 17. Unpaired t-test density and lignin (%) (dry season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	Lignin%	{0}	{3}	7	7	9.66	7.96	1.7	0.4689	1.79	0.0987	Bilateral
Density	Lignin%	{0}	{4}	7	7	9.66	5.8	3.86	0.3571	4.19	0.0013	Bilateral
Density	Lignin%	{0}	{6}	7	7	9.66	7.85	1.81	0.3677	1.96	0.0736	Bilateral
Density	Lignin%	{3}	{4}	7	7	7.96	5.8	2.16	0.8397	2.84	0.0149	Bilateral
Density	Lignin%	{3}	{6}	7	7	7.96	7.85	0.11	0.8561	0.15	0.8836	Bilateral
Density	Lignin%	{4}	{6}	7	7	5.8	7.85	-2.05	0.9833	-2.8	0.016	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 18. Unpaired t-test density and cellulose (%) (dry season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	Cellulose	{0}	{3}	7	7	26.94	20.12	6.82	0.5274	9.45	<0.0001	Bilateral
Density	Cellulose	{0}	{4}	7	7	26.94	23	3.94	0.6131	7.01	<0.0001	Bilateral
Density	Cellulose	{0}	{6}	7	7	26.94	23.29	3.65	0.7436	5.47	0.0001	Bilateral
Density	Cellulose	{3}	{4}	7	7	20.12	23	-2.88	0.2616	-4.27	0.0011	Bilateral
Density	Cellulose	{3}	{6}	7	7	20.12	23.29	-3.17	0.7585	-4.15	0.0013	Bilateral
Density	Cellulose	{4}	{6}	7	7	23	23.29	-0.29	0.4082	-0.47	0.6457	Bilateral

P-values less than 0.05 suggest a significant difference.

3.3.2 Wet season forage analysis results

To measure the forage quality and quantity of kikuyu *(P. clandestinum)* during the wet season (November through March), a total of *n=28* samples were taken. The *n=7* samples were taken from three different densities of *A. koa* groves, as well as from full sun (Table 19). Dry season forage analysis results were produced by the University of

Hawaii Agricultural Diagnostic Service Center measuring a total of 19 different attributes: phosphorus, potassium, calcium, magnesium, sodium, iron, manganese, zinc, copper, boron, dry matter, ash, crude protein, fat, neutral detergent fiber, acid detergent fiber, lignin, cellulose and green weight. Each one of these 19 attributes from each sampling site was paired with the LAI of the canopy above that particular site, yielding a correlative graph and p-value that suggested whether LAI (and thus *A. koa*) had a positive or negative influence on the quality and quantity of forage.

Table 19. Wet season forage analysis of *P. clandestinum* growing at Ulupalakua Ranch, Maui, Hawaii.

			%					ug/g			D.M.%	Ash %	CP%	FAT%	NDF%	ADF%	Lignin%	Cellu%	Fresh
Acacia koa	P	K	Ca	Mg	Na	Fe	Mn	Zn	Cu	B	F1	F2	F3	F4	F5	F6	F7	F8	weight, g
koa 3m #1	0.14	1.69	0.38	0.28	0.04	184	16	187	5	9	23.42	1.78	14.29	1.63	71.25	39.48	12.63	26.84	174.14
koa 3m #2	0.16	1.10	0.46	0.29	0.04	188	15	137	4	8	21.60	2.09	15.73	1.68	68.89	38.21	12.86	25.35	165.47
koa 3m #3	0.17	1.19	0.37	0.27	0.05	173	15	126	4	8	19.75	1.76	15.72	1.55	70.60	38.51	11.78	26.74	160.20
koa 3m #4	0.20	0.98	0.31	0.30	0.06	165	12	136	4	7	19.31	1.96	18.36	2.21	66.28	32.04	8.12	23.92	189.05
koa 3m #5	0.18	0.80	0.44	0.24	0.05	168	15	159	5	7	22.77	2.08	17.49	1.85	70.06	36.37	10.99	25.39	143.15
koa 3m #6	0.14	1.09	0.42	0.23	0.04	332	22	134	5	6	29.08	2.56	15.09	1.76	71.22	38.66	12.18	26.48	171.48
koa 3m #7	0.13	1.23	0.48	0.21	0.04	244	22	55	4	5	23.06	2.10	16.16	1.68	70.61	40.60	12.60	28.00	147.56
koa 6m #1	0.09	1.10	0.28	0.19	0.03	213	11	145	2	3	33.59	2.60	6.33	1.70	76.76	39.87	8.72	31.15	109.32
koa 6m #2	0.11	1.63	0.26	0.19	0.03	139	13	567	3	3	31.38	2.33	8.69	1.68	76.77	39.72	8.80	30.92	111.05
koa 6m #3	0.08	0.92	0.33	0.21	0.03	224	13	228	2	4	39.04	2.62	6.47	1.26	76.50	41.58	8.09	33.50	127.89
koa 6m #4	0.12	1.62	0.27	0.22	0.04	150	11	163	2	4	33.09	2.30	8.54	2.59	74.24	36.96	6.00	30.96	119.73
koa 6m #5	0.09	1.11	0.36	0.26	0.04	168	12	67	3	5	29.10	2.51	6.94	2.34	72.90	38.81	6.32	32.49	115.14
koa 6m #6	0.09	1.09	0.36	0.22	0.03	228	16	102	3	4	40.86	2.78	7.18	1.77	74.56	39.86	8.12	31.74	98.01
koa 6m #7	0.07	0.60	0.28	0.20	0.02	302	17	266	2	3	56.13	3.42	5.89	1.56	76.10	39.96	7.06	32.90	74.11
koa 4m #1	0.25	0.92	0.28	0.26	0.05	101	18	178	4	3	20.82	2.09	17.27	2.65	67.22	32.02	4.42	27.60	88.63
koa 4m #2	0.18	1.53	0.33	0.24	0.05	126	20	366	5	4	27.27	2.20	17.69	2.07	68.53	35.15	7.01	28.13	45.93
koa 4m #3	0.24	1.01	0.28	0.25	0.04	109	22	154	4	3	21.32	2.08	19.40	3.59	61.53	29.34	4.39	24.95	84.86
koa 4m #4	0.20	0.87	0.29	0.23	0.05	107	18	145	4	2	20.63	2.13	16.49	2.82	66.99	32.31	5.40	26.91	122.43
koa 4m #5	0.23	1.63	0.28	0.27	0.10	128	18	235	4	3	18.93	2.09	18.50	2.99	65.15	31.11	5.31	25.81	109.54
koa 4m #6	0.24	1.65	0.29	0.27	0.07	123	21	103	3	3	20.75	2.21	16.02	3.20	65.99	31.95	5.16	26.79	127.30
koa 4m #7	0.20	1.67	0.35	0.28	0.10	125	17	415	4	4	21.73	2.14	16.57	3.19	67.21	32.07	4.93	27.14	127.81
Full Sun	0.12	0.86	0.27	0.16	0.02	238	14	250	3	2	40.06	2.89	5.34	0.92	79.10	43.41	9.29	34.12	70.76
Full Sun	0.08	0.63	0.24	0.16	0.02	228	19	59	3	1	50.81	3.80	4.98	1.32	77.75	40.88	9.39	31.49	95.19
Full Sun	0.08	0.56	0.27	0.17	0.02	214	16	207	2	2	50.98	3.30	4.58	0.94	76.93	42.17	10.20	31.97	77.71
Full Sun	0.10	0.64	0.34	0.19	0.02	283	25	290	3	3	59.00	4.21	6.06	1.38	75.92	44.09	11.18	32.91	74.88
Full Sun	0.10	0.83	0.30	0.21	0.02	201	12	424	2	2	42.07	2.67	5.45	1.32	77.15	40.05	7.60	32.44	115.51
Full Sun	0.08	0.46	0.29	0.20	0.02	308	15	392	2	2	49.30	3.53	4.65	1.15	78.32	41.12	8.96	32.16	110.45
Full Sun	0.10	0.74	0.29	0.19	0.02	297	25	355	4	3	39.86	2.59	5.76	1.03	79.06	41.44	8.37	33.07	104.35

3.3.3 Wet season forage statistical analysis

Forage analysis results from the University of Hawaii at Manoa were input into the statistical software InfoStat (Di Rienzo *et al.* 2016) to analyze potential relationships. Lineal regression, and coefficients of correlation, with p-value $\leq .05$, were determined with the software to see whether statistically significant correlations existed. Pearson's correlation coefficient was also utilized to measure the statistical relationship between these variables, by method of covariance (Table 20). The following attributes of kikuyu were determined to be *correlated* with the LAI of *A. koa* (via Pearson's correlation) with a p-value ≤ .05: phosphorus, potassium, calcium, magnesium, sodium, iron, copper, boron, dry matter, ash, crude protein, fat, neutral detergent fiber, acid detergent fiber and cellulose. The following attributes of kikuyu were determined *not* to be correlated with the LAI of *A. koa* (via Pearson's correlation) with a p-value ≤ .05: manganese, zinc, lignin, green weight. Graph and table representations attributes of kikuyu forage analysis in relation to the LAI of *A. koa* from the wet season can be found in the appendix (Figures A.9 to A.23, tables A.13 to A. 27)

In the wet season, there were significant correlations between yield of kikuyu and LAI (p-value = .0001), and a significant relationship between dry matter and LAI (p-value= .0001). There were also significant connections between the LAI of *A. koa* and crude protein, ADF (acid detergent fiber), NDF (neutral detergent fiber) and cellulose. All of these attributes had a p-value of .0001 and can be found in Figures A.19, A.21, A. 22 and A.23 in the appendix. Unlike results from the dry season, there were no significant relationship between lignin and LAI of *A. koa* in the wet season. This could be attributable to the lessening of dry and woody material of kikuyu during the rainy season, with higher levels of new growth.

Table 20. Pearson correlation analysis of relationships between kikuyu forage attributes and LAI of koa in the wet season.

Pearson correlation *(wet season)*

Variable(1)	Variable(2)	n	Pearson	p-value
Phosphorus % Kikuyu	LAI Acacia koa	28	0.77	0.0001
Potassium % Kikuyu	LAI Acacia koa	28	0.54	0.0032
Calcium % Kikuyu	LAI Acacia koa	28	0.42	0.0263
Magnesium % Kikuyu	LAI Acacia koa	28	0.68	0.0001
Sodium % Kikuyu	LAI Acacia koa	28	-0.58	0.0013
Iron ug/g Kikuyu	LAI Acacia koa	28	-0.58	0.0013
Manganese u/ug Kikuyu	LAI Acacia koa	28	0.24	0.2131
Zinc u/ug Kikuyu	LAI Acacia koa	28	-0.31	0.1123
Copper u/ug Kikuyu	LAI Acacia koa	28	0.69	0.0001
Boron u/ug Kikuyu	LAI Acacia koa	28	0.38	0.0455
D.M% Kikuyu	LAI Acacia koa	28	**-0.81**	0.0001
Ash % Kikuyu	LAI Acacia koa	28	**-0.71**	0.0001
Crude Protein % Kikuyu	LAI Acacia koa	28	**0.88**	0.0001
Fat % Kikuyu	LAI Acacia koa	28	0.68	0.0001
NDF % Kikuyu	LAI Acacia koa	28	**-0.85**	0.0001
ADF % Kikuyu	LAI Acacia koa	28	**-0.72**	0.0001
Lignin % Kikuyu	LAI Acacia koa	28	-0.2	0.3175
Cellulose % Kikuyu	LAI Acacia Koa	28	**-0.78**	0.0001
Green weight(g) Kikuyu	LAI Acacia koa	28	0.26	0.1754

P-values less than .05 suggest a relationship between the two variables. P-values exceeding .05 suggest that no statistically significant relationships between the two variables exist.

The implications of these results for sustainable cattle production in Hawaii are many, for both the dry and the rainy season, particularly in the drier leeward slopes of upper-elevation ranches whose principal forage is kikuyu. Attributes of forage quality such as phosphorus and calcium increased under koa. While often overlooked, these micronutrients are important for the growth and health of cattle (Ternouth 1990).

Attributes of digestibility and yield of forage tended to improve under all densities of koa versus full sun (no trees), with the exception of yield during the rainy season. This decrease in yield could be attributable to low light levels under the canopy, discouraging robust growth. An unpaired t-test confirmed that there were significant decreases in yield (Table 22). However, yield (or availability) of kikuyu during the dry season did not decrease, perhaps because the presence of trees increased water retention during acute drought conditions. This could lessen the impact of drought on Ulupalakua Ranch and other Upcountry Maui ranches. There were notable increases in markers of forage quality such as CP, NDF, ADF, lignin and cellulose (Tables 23, 24, 25, 26, 27). All of these apparent increases in quality should be further investigated in a larger context of grazing trials to better understand the potential benefits of koa silvopastoral systems. In addition to potential increases in the efficiency and sustainability of ranching operations, ranchers and the community at large, will benefit from the positive environmental impacts of more native tree cover.

To better understand forage attributes of kikuyu growing under koa during wet and dry seasons, averages of yield, crude protein, NDF, ADF, lignin and cellulose can be seen from kikuyu growing under three densities of koa versus. kikuyu growing in full sunlight. Yield of kikuyu during the dry season and wet season was slightly higher under koa versus full sun. This result is different from results found by (Grace 1995) in his study on kikuyu and koa, in which biomass of kikuyu increased with light transmission. This difference could be attributable to differences in climactic conditions (Grace´s study took place on the eastern slopes of the Big Island, whereas the Ulupalakua study was done on the southwestern slopes of Maui). Crude protein (measured as nitrogen content) was markedly higher under koa in both the wet season and dry season. This is consistent with results found in studies investigating the effect of shade cloth (Samarakoon *et al*. 1990). NDF, ADF, lignin and cellulose tended to be lower in kikuyu growing beneath koa (Tables A.21, A.22, A.23). This trend existed in both the dry season and the wet season. Lower values of NDF, ADF and lignin are indicative of higher forage quality. Average yields of these markers can be found in Table 21.

Table 21. Average yield (g/m2), crude protein (%), NDF (%), ADF (%) lignin (%) and cellulose (%) of kikuyu during dry season and wet season. "Under shade" (under the canopy of koa) represents an average of three densities of koa (3, 4 and 6 m). "Full sun" represents kikuyu growing in open pasture without the influence of koa trees.

	Dry Season		**Rainy Season**	
Variable	Under shade (koa canopy)	Full sun	Under shade (koa canopy)	Full sun
yield (g/m2)	796 g/m2	708 g/m2	497.67 g/m2	370.77 g/m2
crude protein %	13.83%	5.88%	13.56%	5.26%
neutral detergent fiber %	62.41%	68.42%	70.45%	77.75%
acid detergent fiber %	29.34%	36.60%	36.41%	41.88%
Lignin %	7.20%	9.66%	8.14%	9.28%
Cellulose %	22.13%	26.94%	28.27%	32.59

Table 22. Unpaired t-test density and yield (g/m^2) (wet season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	Yield g/m2	{0}	{3}	7	7	370.77	657.74	-286.97	0.7392	-7.85	<0.0001	Bilateral
Density	Yield g/m2	{0}	{4}	7	7	370.77	403.71	-32.94	0.2532	-0.62	0.5463	Bilateral
Density	Yield g/m2	{0}	{6}	7	7	370.77	431.57	-60.8	0.9234	-1.59	0.1381	Bilateral
Density	Yield g/m2	{3}	{4}	7	7	657.74	403.71	254.03	0.1462	4.96	0.0003	Bilateral
Density	Yield g/m2	{3}	{6}	7	7	657.74	431.57	226.18	0.8125	6.33	<0.0001	Bilateral
Density	Yield g/m2	{4}	{6}	7	7	403.71	431.57	-27.85	0.2175	-0.53	0.6054	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 23. Unpaired t-test density and CP (%) (wet season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	CP%	{0}	{3}	7	7	5.26	16.12	-10.86	0.0415	-19.2	<0.0001	Bilateral
Density	CP%	{0}	{4}	7	7	5.26	17.42	-12.16	0.0804	-24.2	<0.0001	Bilateral
Density	CP%	{0}	{6}	7	7	5.26	7.15	-1.89	0.1268	-4.1	0.0015	Bilateral
Density	CP%	{3}	{4}	7	7	16.12	17.42	-1.3	0.7374	-1.87	0.0864	Bilateral
Density	CP%	{3}	{6}	7	7	16.12	7.15	8.97	0.5615	13.45	<0.0001	Bilateral
Density	CP%	{4}	{6}	7	7	17.42	7.15	10.27	0.8046	16.75	<0.0001	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 24. Unpaired -t-test density and NDF (%) (wet season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	NDF%	{0}	{3}	7	7	77.75	69.84	7.9	0.3426	9.87	<0.0001	Bilateral
Density	NDF%	{0}	{4}	7	7	77.75	66.09	11.66	0.1321	12.06	<0.0001	Bilateral
Density	NDF%	{0}	{6}	7	7	77.75	75.4	2.34	0.5512	3.24	0.0071	Bilateral
Density	NDF%	{3}	{4}	7	7	69.84	66.09	3.76	0.5545	3.45	0.0048	Bilateral
Density	NDF%	{3}	{6}	7	7	69.84	75.4	-5.56	0.7176	-6.33	<0.0001	Bilateral
Density	NDF%	{4}	{6}	7	7	66.09	75.4	-9.32	0.345	-9.03	<0.0001	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 25. Unpaired -t-test density and ADF (%) (wet season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	ADF%	{0}	{3}	7	7	41.88	37.7	4.18	0.1291	3.51	0.0043	Bilateral
Density	ADF%	{0}	{4}	7	7	41.88	31.99	9.89	0.6693	11.64	<0.0001	Bilateral
Density	ADF%	{0}	{6}	7	7	41.88	39.54	2.34	0.949	3.09	0.0094	Bilateral
Density	ADF%	{3}	{4}	7	7	37.7	31.99	5.7	0.2628	4.58	0.0006	Bilateral
Density	ADF%	{3}	{6}	7	7	37.7	39.54	-1.84	0.1151	-1.55	0.1462	Bilateral
Density	ADF%	{4}	{6}	7	7	31.99	39.54	-7.54	0.6239	-8.98	<0.0001	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 26. Unpaired t-test density and lignin (%) (wet season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	Lignin%	{0}	{3}	7	7	9.28	11.59	-2.31	0.4175	-3.01	0.0108	Bilateral
Density	Lignin%	{0}	{4}	7	7	9.28	5.23	4.05	0.5075	7.32	<0.0001	Bilateral
Density	Lignin%	{0}	{6}	7	7	9.28	7.59	1.7	0.9379	2.76	0.0174	Bilateral
Density	Lignin%	{3}	{4}	7	7	11.59	5.23	6.36	0.1493	8.96	<0.0001	Bilateral
Density	Lignin%	{3}	{6}	7	7	11.59	7.59	4.01	0.3754	5.28	0.0002	Bilateral
Density	Lignin%	{4}	{6}	7	7	5.23	7.59	-2.36	0.5578	-4.34	0.001	Bilateral

P-values less than 0.05 suggest a significant difference.

Table 27. Unpaired t-test density and cellulose (%) (wet season).

Clasific	Variable	Group 1	Group 2	n(1)	n(2)	Mean(1)	Mean(2)	Mean(1)-(2)	pHomVar	T	p-value	Test
Density	Cellulose	{0}	{3}	7	7	32.59	26.1	6.49	0.3215	10.86	<0.0001	Bilateral
Density	Cellulose	{0}	{4}	7	7	32.59	26.76	5.83	0.6089	11.19	<0.0001	Bilateral
Density	Cellulose	{0}	{6}	7	7	32.59	31.95	0.64	0.6856	1.27	0.2289	Bilateral
Density	Cellulose	{3}	{4}	7	7	26.1	26.76	-0.66	0.624	-1.02	0.3272	Bilateral
Density	Cellulose	{3}	{6}	7	7	26.1	31.95	-5.85	0.5508	-9.23	<0.0001	Bilateral
Density	Cellulose	{4}	{6}	7	7	26.76	31.95	-5.19	0.9142	-9.24	<0.0001	Bilateral

P-values less than 0.05 suggest a significant difference.

3.4 Conclusions

Sampling during the wet and dry season, with subsequent statistical analysis, yielded results that confirmed that there are in fact significant differences between *P. clandestinum* growing beneath *A. koa* versus *P. clandestinum* growing in full sun without the ecosystem services rendered by koa. These ecosystem services provided by koa would include dappled shade, the capture and retention of moisture, nitrogen fixation, nutrient cycling and habitat for biodiversity (Dubeaux *et al.* 2017). It is likely that all these ecosystem services combined were factors in the growth of kikuyu. The cycling of nutrients from lower strata of the soil by the roots of *A. koa* could be significant factor, as has been seen in system ecology and its relation to soil health (Jenny 1980). The interpretation of these results based upon available literature is complex given that regardless of results yielded from forage analysis in a laboratory, additional factors must be considered, such as secondary compounds, anti-quality components and toxins found in *P. clandestinum* under certain conditions (Allen and Segarra 2001). Values found in forage analysis, particularly dry matter, crude protein, NDF, ADF, lignin and cellulose, are indicative of a higher value of forage quality (Marais 2001) and are consistent with other studies on kikuyu in which forage quality increases to an extent under conditions of shade and then loses digestibility and intake (at least among sheep) as the "leaf to stem" ration decreases (Samarakoon 1987).

Anecdotal evidence from the Big Island of Hawaii has suggested that cattle will often prefer kikuyu growing in full sun (which may have something to do with an overaccumulation of nitrogen in kikuyu growing under *A. koa*, particularly after a heavy rain). Tests for such anti-nutrient compounds do not exist in the state of Hawaii, therefore we decided to focus on the following forage attributes of koa: phosphorus, potassium, calcium, magnesium, sodium, iron, manganese, zinc, copper, boron, dry matter, ash, crude protein, fat, neutral detergent fiber, acid detergent fiber, lignin, cellulose and forage availability measured in weight.

Studies from the Big Island of Hawaii used a different methodology of kikuyu forage analysis, in which forage quality was estimated by measuring nitrogen content and *in vitro* dry matter digestibility (Grace 1995). In these studies, nitrogen content increased as light transmission decreased. The digestible dry matter of kikuyu was optimized under moderate shading. Biomass decreased significantly beneath a dense koa canopy. These relationships were present within our experiment as well, with medium densities typically demonstrating increases in forage quality and micronutrients, while not compromising biomass to an overly harmful degree. *A. koa* fixes nitrogen, which was evident in high N (crude protein) of forage samples taken beneath koa. On the floor of mesic Hawaiian forests, koa phyllodes decompose, cycling nutrients back into the soil. (Whitesell 1990).

Although forage analysis data is indicative of increases in certain nutrients, these forage attributes would need validation with grazing trials to confirm potential benefits. However, if we look through a lens of established literature on *P. clandestinum*, it is possible to suggest that increases in certain attributes would lead to higher quality forage. There is well-established evidence that nutrients such as P, K, Ca, Ma, Mg, S, Fe, Zn, Cu and Bo are necessary and beneficial to the growth, weight gain, and finishing quality of cattle (Ternouth 1990; Tizioto *et al.* 2014). Our samples demonstrated that there were statistically significant increases in all of these nutrients with the exception of manganese and zinc. There is also ample literature regarding ash, crude protein, fat, NDF, ADF, lignin and cellulose in kikuyu (Marais 2001). Decreases in attributes such as NDF are typically indicative of higher forage quality and digestibility. High levels of crude protein/nitrogen can lead to decreases in quality. In the tropical highlands of Costa Rica, researchers found that crude protein percentages of kikuyu exceeding 14% were not optimal for digestion (Sanchez and Soto 1992). It is possible that cattle can selectively graze from areas beneath the trees as well as areas of open sun if the system is designed correctly, which may mitigate any of the negative effects of high nitrogen content. Any conclusions regarding kikuyu under koa should be nuanced considering that tannins, oxalates, other secondary compounds and high levels of nitrogen can all decrease palatability of a forage (Allen and Segarra 2001). More investigation on this theme is necessary to better understand the intake of kikuyu forage by cattle in a koa-based silvopastoral system, rather than just relying on forage analysis lab results.

4 Qualitative surveys with Maui ranchers and government extension agents regarding potential benefits and species for reforestation in a silvopastoral context

4.1 Introduction

The third objective of our investigation emphasized the knowledge and opinions of ranchers and land managers regarding silvopastoral systems, as well as various native and non-native tree species in relation to ranching. Most interviewees were based on Maui ranches, with two exceptions of government-sector land managers (Natural Resources Conservation Service of the USDA and Department of Hawaiian Homelands) based on the Big Island of Hawaii that were involved in decision making that would potentially affect management practices on Maui ranches. Ranch sizes were as follows for participants: Hokunui (238 acres/96 ha), Ulupalakua Ranch (11,051 acres/4,472 ha) and Haleakala Ranch (29,000 acres/11,735 ha).

4.2 Methodology

Seven participants were asked to classify their perception of the benefit of trees to ranching systems on a positive scale of 1 to 5, with 1 being a very low impact and 5 being a very high impact (Table 28). Five of these participants were ranch managers and two were from governmental agencies (Natural Resources Conservation Service of the USDA and the Department of Hawaiian Homelands). The goal of objective 3 was to understand the perceptions of members of ranches located on the leeward slopes of Haleakala, with the ultimate goal of developing silvopastoral strategies appropriate for the microclimates of Maui. This involved surveys with ranch managers and extension agents from the USDA and Department of Hawaiian Homelands. Answers were classified numerically and then input into a spreadsheet to be able to take a mode. The same participants were also asked to name native and non-native tree species that they considered to be helpful or deleterious to cattle. Names of species could be provided in Hawaiian, English or by their Latin name.

Table 28: Scale rating the extent to which native trees in pastures can help in the resiliency/productivity of ranches.

SCALE	
None	0
Very Low	1
Low	2
Moderate	3
High	4
Very High	5

4.3 Results and Discussion

Results were mixed in regard to value that different members of the ranching community place on silvopastoral systems or sporadic trees within the ranching landscape. A member of Ulupalakua Ranch as well as the head of planning for ´Aina Mauna Department of Hawaiian Homelands believed that the integration of trees into the landscape had overwhelmingly positive benefits and could mitigate many of the effects of drought and climate-change. It is notable that while some ranchers and land managers did not assign high values to all categories, *all* assigned at least one score of 5 to a category. It is noteworthy that Haleakala Ranch and Hokunui Ranch receive significantly more rain than Ulupalakua Ranch, which is more vulnerable to seasonal and long-term drought. This could explain differences in opinion regarding the categories *dry summers, out of season dry spells, changes in rain patterns, increases in average temperatures* and *heat waves.* For example, members of Ulupalakua Ranch considered native trees to have a “very high” and “moderate” positive impact on the mitigation of heat waves, whereas land managers from Haleakala Ranch and Hokunui Ranch assigned 0 to this category. Results can be interpreted as a matter of opinion and a matter of the microclimates of each ranch. Nonetheless, an overarching theme was that native trees, particularly *A. koa*, can have positive impacts on ranching operations, with particularly positive benefits for drought and heat mitigation. Results can be seen in Table 29. Multimodal responses occurred in more than one category.

We also asked which tree species were beneficial or deleterious to their ranching strategies. There were several species that are highly invasive, noxious and problematic for ranching (Table 30). On the other hand, there are a number of tree species, both native and non-native, that are considered beneficial on Hawaiian ranches.

Table 29: Survey format describing the extent to which trees/reforestation can mitigate specific risks present in the ranching operation, with 1 having "very low" impact, and 5 having "very high" impact.

Category	Challenge/ Danger	NCRS	Ulupalakua Ranch (Diana Crowe)	Ulupalakua Ranch (Kaimi)	Ulupalakua Ranch (Kristen Mack)	Haleakala Ranch (Jordan Jokiel)	Hokunui Ranch (Koa Hewahewa)	DHHL
Changes in Precipitation	Winter/ Kona Storms	2	5	3	4	1	3	3
	Dry Summers	4	5	5	4	3	5	5
	Out of season dry spells	4	5	5	4	3	4	5
	Changes in Rain Patterns	2	5	4	2	4	4	5
	Intense Rainstorms	3	5	3	4	2	2	3
	Tropical Storms/ hurricanes	0	5	3	2	1	1	2
Changes in Temperature	Increases In Average Temperature	4	5	4	3	3	1	5
	Heat Waves	5	5	3	3	0	0	3
Problems in soil productivity	Flooding	1	5	5	4	3	4	3
	Soil Erosion	2	5	5	5	4	5	4
	Topsoil Loss	2	5	5	5	4	5	4
Others	Caloric stress of the herd	3	5	4	4	4	4	0
	Wild Fires	0	5	2	2	4	4	3
	Strong Winds	3	5	3	3	5	4	3

*NRCS—Natural Resources Conservation Service
*DHHL— Department of Hawaiian Homelands

Table 30: List of useful and harmful tree species (both native and non-native) found on upper-elevation ranches in Maui, Hawaii.

N°	Questions	Answers
1	What are some of the tree species that you have that provide benefit to the cattle (whether it be shade, food, improvement in the quality of the pasture? (native species are in bold print)	**A'ali'i *(Dodonaea viscosa)— shade, native biodiversity*** Albizzia (**not** recommended) *(Falcataria moluccana)—shade, nitrogen fixation* Eucalyptus *(Eucalyptus globulus, Eucalyptus robusta)—shade, usable lumber* Haole Koa *(Leucaena leucocephala)—dry season fodder, nitrogen fixation* **Iliahi *(Santalum ellipticum)—shade, native biodiversity*** Kiawe *(Prosopis pallida)—fodder, nitrogen fixation, shade* **Koa *(Acacia koa)—native biodiversity, nitrogen fixation, shade, lumber*** Kukui *(Aleurites moluccanus)—shade, cultural value* **Mamane *(Sophora chrysophylla)—****native biodiversity, shade* Monkey pod *(Samanea saman)—shade, lumber, nitrogen fixation* **Ohia *(Metrosideros polymorpha)—****native biodiversity, cultural value, shade* **Wiliwili *(Erythrina sandwicensis)****—drought mitigation, native biodiversity, shade, nitrogen fixation, cultural value*
2	What are some of the tree or plant species that affect the herd negatively?	Albizzia *(Falcataria moluccana)* Black Wattle *(Acacia mearnsii)* Bocconia *(Bocconia frutescens)* Christmas Berry *(Schinus terebinthifolius)* Eucalyptus *(Eucalyptus globulus, Eucalyptus robusta)* Gorse *Ulex europaeus* Guava *(Psidium guajava, Psidium cattleyanum)* Gunpowder tree *(Trema orientalis)* Ironwood *(Casuarina equisetifolia)* M. faya *(Myrica faya)* Melochia *(Melochia umbellata)* Monterey Pine *(Pinus radiata)* Silver oak *(Grevillea robusta)* Tropical ash *(Fraxinus udei)*

4.4 Conclusions

Through objective 3, we sought to better understand the perceptions of ranchers and land managers about trees in the ranching landscape. We learned that land managers agree that there are significant benefits to silvopastoral systems and interspersed trees in the landscape. Trees within the ranching landscape have been demonstrated to mitigate the effects of drought and heat waves. Silvopastoral buffers along streams have also been shown to increase water quality (Chará *et al.* 2007). Native reforestation at the nearby Auwahi Forest Restoration Site has also been effective in increasing the absorptive qualities of soil for moisture retention (Perkins *et al.* 2014). It is noteworthy that there were significant differences in the responses of ranchers from dry leeward areas versus members of Hokunui Ranch and Haleakala Ranch, whose territory is exposed to more rain and less drought conditions.

We would suggest that introduced species that are beneficial to ranching operations be used sparingly and judiciously to make sure they do not become more invasive. These nitrogen-fixing species include haole koa (*Leucaena leucocephala*), kiawe (*Prosopis pallida*) and monkeypod (*Samanea saman*). The proper management of these species provides shade, forage and the potential fertilization of other adjacent species.

Of the 14 species mentioned as having a negative impact toward cattle operations, none were endemic native species. Out of the 12 species mentioned as having a positive impact toward cattle operations, 6 of these species were endemic to the Hawaiian Islands. These 6 species include a’ali’i *(Dodonaea viscosa),* ‘iliahi *(Santalum ellipticum),* koa *(Acacia koa),* mamane *(Sophora chrysophylla),* ohi’a *(Metrosideros polymorpha)* and wiliwili *(Erythrina sandwicensis).* The mention of the Hawaiian tree wiliwili by members of Ulupalakua Ranch is indicative of its importance on the dry leeward slopes of Haleakala. It is noteworthy that other *Erythrina* species are extensively used in Central America for silvopastoral agroforestry systems (Jose and Dollinger 2019). Future studies could consider the incorporation of other native species into ranching systems to mitigate environmental degradation and sensitivities to climate change. The incorporation of native species is also important for genetic biodiversity and as habitat for native animals (Pejchar *et. al.* 2005).

We would suggest the integration of these beneficial species as much as possible into the ranching landscape, particularly *A. koa*, given its proven benefits in silvopastoral systems (Grace 1995). Intercropping (even in silvopastoral systems) is likely to increase efficiencies in land use (Riley 1984). Tree cover has also been shown to lessen the caloric stress of the herd, resulting in higher productivity (Villanueva *et al.* 2008). As illustrated in sections 2 and 3 of this thesis, planting *A. koa* at an optimal density ensures that tree form as well as forage performance are not negatively affected. In regard to tree form, potential carbon sequestration and potential for the harvest of merchantable lumber, this study illustrated that a planting of koa trees at distances of 4 m may be preferable to a closer spacing (3 m). Since the caloric expenditures of cattle during times of drought and heat are known to increase (Broom *et al*. 2013), establishing more non-allelopathic trees on any dryland ranches is likely to increase efficiency. More multidisciplinary investigation is necessary to better understand the benefits of silvopastoral systems on the leeward slopes of Haleakala.

4.4.1 Economic potential for the sustainable harvest of koa lumber

Koa wood is economically valuable and has been of great use since ancient Hawaiian times for the construction of canoes, paddles, housing and various other implements (Bishop Museum 2020). Since the arrival of the first herd of cattle and goats with Captain George Vancouver in 1793, many of the formerly vast koa forests have been cleared for cattle ranching (Fischer 2007). While limited private landowners have reforested on a small scale, it has been within the past three decades that the state of Hawaii has created incentives and programs for the reforestation of koa for both conservation and commercial purposes. Great efforts have been made to emphasize the sustainable harvest of koa, with state and conservation easements only harvesting from dead or dying trees (Creamer 2019) With a relative decrease in supply and a great increase in demand, the price of koa has skyrocketed in recent years, with common grade koa selling for USD 30/board foot and curly instrument-grade koa selling for as much as USD 125/board foot (personal correspondence with Brian Green, Pacific American Lumber, January 10, 2020). With such high prices, landowners, including ranches in high-elevation regions of Maui and the Big Island, have begun to consider koa timber plantations and the incorporation of *A. koa* into silvopastoral systems as a way of increasing the financial viability of their operations.

Various scenarios for land management with koa were weighed against each other in a study by (Goldstein *et al.* 2006**),** in which investigators considered the net present value (NPV) of koa growing systems. They found that with current prices, land values, taxes and government incentives/subsidies, it made the most financial sense to focus exclusively on the growth of koa in a plantation or conservation setting, simultaneously excluding ungulates from the operation. Nonetheless, their project verified that silvopastoral ranching systems incorporating *A. koa* have a positive NPV, particularly if cattle were excluded from the area in which the juvenile trees were planted for a minimum of seven years, to let the trees reach and adequate size (personal communication with Dr. J.B. Friday, head extension forester, state of Hawaii, January 7, 2020).

Literature from *A. koa* silvopasture on the Big Island elucidates some of the benefits and potential pitfalls of integrating koa and kikuyu. In his study on the modeling of koa growth within *P. clandestinum* pasturelands at Keauhou Ranch, Grace (1995) found that ¨grazing of koa early in stand development reduced leaf area index and harvestable volumes but allowed greater grass production.¨ Young koa was extremely vulnerable to grazing from cattle, and any opportunities for merchantable wood were greatly reduced by introduction of the herd in the early stages of koa growth. Modeling used in the Big Island study also highlighted the difficulty of estimating the marketable volume of timber harvests since it is not correlated with average tree size or total stand biomass but rather size-class distribution within stands.

The *A. koa* trees within much of the system at Pu’u Makua at Ulupalakua Ranch on Maui are not yet of harvestable age and size and are unlikely to be harvested since they are part of a conservation easement. Nonetheless, *A. koa* planted in adjacent grazing area would grow at a similar form and rate. Trees in zone 2 were planted about 2001, yet we would still not be able to produce an estimate of merchantable lumber based upon a sample size of n=7 and without destructive sampling. The diameter at breast height of the sampled koa from zone 2 trees ranged from 9.20 cm to 35.00c m (see Table 6); height to the first fork was also measured. Allometric equations based upon Maui *A. koa* were applicable for estimates of carbon sequestration and could be considered for merchantable lumber once the trees are larger (Conrad 2005).

Koa sapwood has very little economic value, while koa heartwood is of great merchantable value. It is difficult (and inaccurate) to estimate merchantable heartwood at any given site without destructive sampling, which would involve taking destructive samples of trees (personal correspondence with Nicklos Dudley, University of Hawaii forester, September 30, 2019). Without a greater frame of reference, we would still suggest planting koa at 3 m and then selectively thin trees to estimate heartwood. Given that it would be difficult to estimate future lumber harvests for this particular site without destructive sampling, it is useful to refer to established literature showing the potential profitability of *A. koa* in a silvopastoral context. Multiple land-use scenarios were examined in a koa conservation case study (Goldstein *et al.* 2006), which compared the NPV (USD/acre) of seven different potential land uses. They found that while *Timber + Subsidy 1 + Cattle* had a positive mean NPV ($USD 596/acre) exceeding an opportunity cost of only ranching cattle (mean NPV of USD 194/acre), it still had a significantly lower NPV than focusing only on *Timber + Subsidy*, which had a mean NPV of USD 671/acre. At a glance, it would appear that using land solely for timber (with the current state of Hawaii subsidy) would be superior to integrating *Timber + Subsidy + Cattle*. However, *Timber + Subsidy* has a potential for negative cash flow in the beginning stages of the investment, while *Timber + Subsidy + Cattle* has the potential to generate cash flow in the initial years of the project (as long as cattle are prevented from damaging juvenile trees). If landowners would like to emphasize timber production over cattle production, we would suggest the establishment of koa planted within pasturelands at a density of 4 m.

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6 APPENDIX

Table A.1. *A. koa* diameter at breast height descriptive statistics.

Variable	n	Mean	S.D.	Mín	Máx
Acacia koa **3m** DBH (cm)	7	22.89	8.64	9.20	35.00

Variable	n	Mean	S.D.	Mín	Máx
Acacia koa **6m** DBH (cm)	7	11.03	1.69	9.00	13.00

Variable	n	Mean	S.D.	Mín	Máx
Acacia koa **4m** DBH (cm)	7	17.21	4.29	10.50	24.00

Table A.2. *A. koa* height at first fork descriptive statistics.

Variable	n	Mean	S.D.	Mín	Máx
Koa **3m** first fork height (cm)	7	119.43	73.68	58.00	274.00

Variable	n	Mean	S.D.	Mín	Máx
Koa **6m** first fork height (cm)	7	126.71	21.80	86.00	149.00

Variable	n	Mean	S.D.	Mín	Máx
Koa **4m** first fork height (cm)	7	167.29	34.72	127.00	218.00

Table A.3. *A. koa* height descriptive statistics.

Variable	n	Mean	S.D.	Mín	Máx
Koa **3m** height (m)	7	7.71	1.66	4.20	9.10

Variable	n	Mean	S.D.	Mín	Máx
Koa **6m** height (m)	7	3.64	0.52	3.00	4.40

Variable	n	Mean	S.D.	Mín	Máx
Koa **4m** height (m)	7	5.19	0.72	4.10	6.20

Table A.4. *A. koa* carbon stock estimate descriptive statistics.

Variable	n	Mean	S.D.	Mín	Máx
Koa **3m** carbon stock estimate(kg)	7	113.44	92.03	8.70	272.55

Variable	n	Mean	S.D.	Mín	Máx
Koa **6m** carbon stock estimate(kg)	7	14.45	5.55	8.22	21.21

Variable	n	Mean	S.D.	Mín	Máx
Koa **4m** carbon stock estimate(kg)	7	48.46	28.98	12.23	103.05

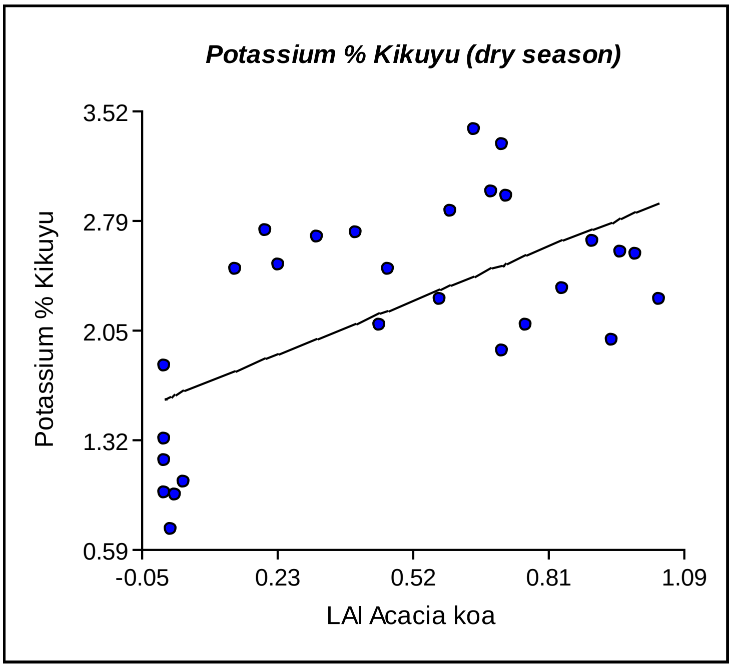

Figure A.1. Dry-season potassium (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.5. Statistical analysis for relationship between LAI of *A. koa* and dry-season potassium (%) in kikuyu. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Potassium % Kikuyu	28	0.38	0.36	0.4	53.43	57.43

Coefficients of regression						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	1.6	0.19	1.21	1.98	8.56	<0.0001
LAI Acacia koa	1.26	0.31	0.62	1.91	4.01	0.0004

ANOVA					
F.V.	SC	gl	CM	F	p-value
Model	5.53	1	5.53	16.12	0.0004
LAI Acacia koa	5.53	1	5.53	16.12	0.0004
Error	8.92	26	0.34		
Total	14.45	27			

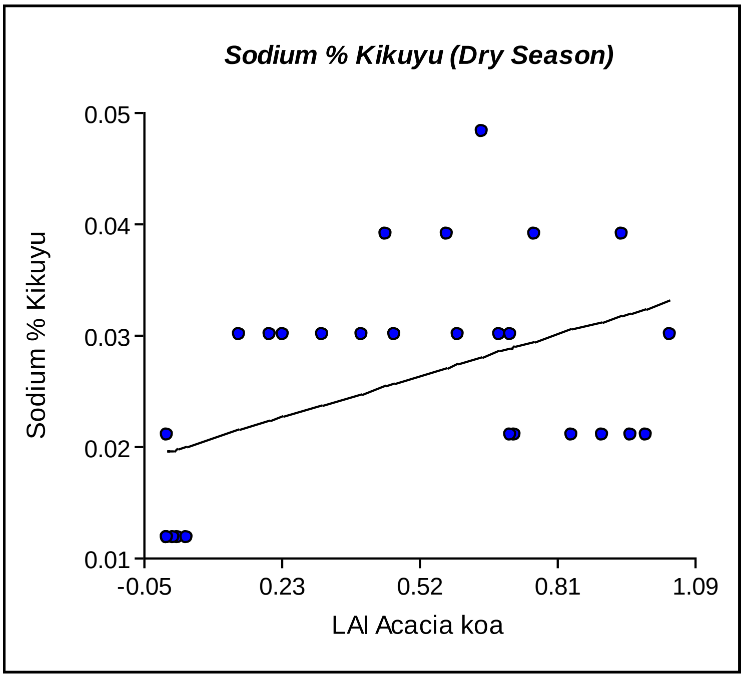

Figure A.2. Dry-season sodium (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.6. Statistical analysis for relationship between LAI of *A. koa* and dry-season sodium (%) in kikuyu. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Sodium % Kikuyu	28	0.22	0.19	1.10E-04	-174.71	-170.72

Coefficients of regression						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.02	3.20E-03	0.01	0.03	5.83	<0.0001
LAI Acacia koa	0.01	0.01	3.40E-03	0.03	2.69	0.0125

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	7.20E-04	1	7.20E-04	7.21	0.0125
LAI Acacia koa	7.20E-04	1	7.20E-04	7.21	0.0125
Error	2.60E-03	26	9.90E-05		
Total	3.30E-03	27			

Coefficients of correlation				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
Na % Kikuyu	LAI Acacia koa	28	0.47	0.0125

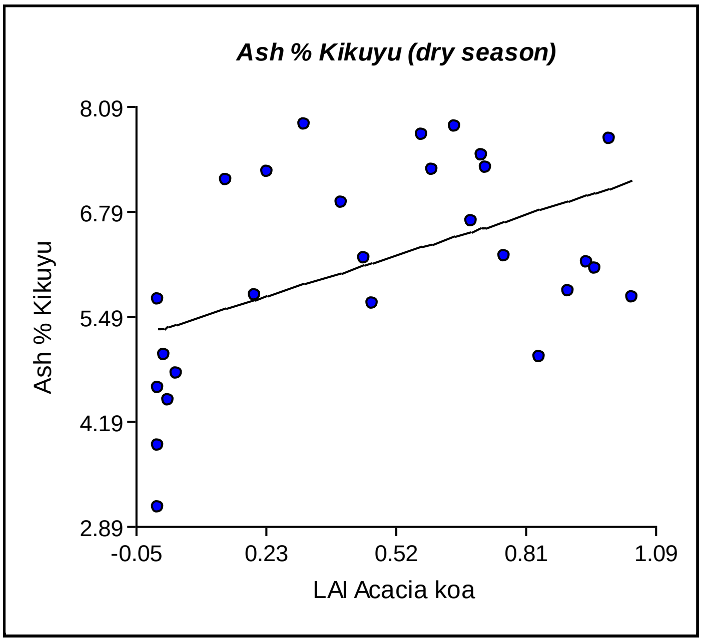

Figure A.3. Dry-season ash (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.7. Statistical analysis for relationship between dry-season ash (%) in kikuyu and LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Ash % Kikuyu	28	0.24	0.21	1.54	91.08	95.08
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	5.33	0.37	4.58	6.08	14.57	<0.0001
LAI Acacia koa	1.76	0.61	0.5	3.03	2.86	0.0082
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Model	10.79	1	10.79	8.2	0.0082	
LAI Acacia koa	10.79	1	10.79	8.2	0.0082	
Error	34.23	26	1.32			
Total	45.02	27				
Coefficients of correlation						
Pearson correlation						
Variable(1)	Variable(2)	n	Pearson	p-value		
Ash % Kikuyu	LAI Acacia koa	28	0.49	0.0082		

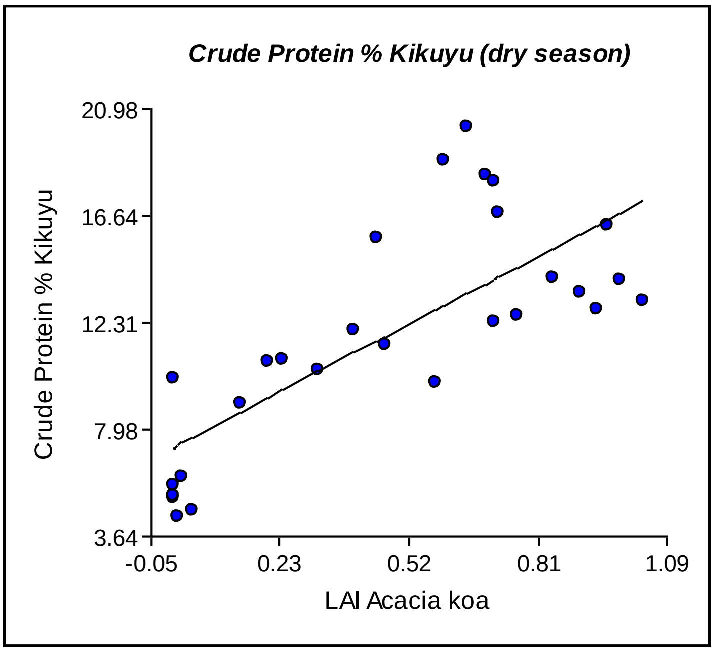

Figure A.4. Dry-season crude protein (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.8. Dry-season crude protein (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Crude Protein % Kikuyu	28	0.57	0.56	10.54	145.52	149.52
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	7.25	0.97	5.27	9.24	7.51	<0.0001
LAI Acacia koa	9.58	1.63	6.24	12.92	5.89	<0.0001
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Model	319.47	1	319.47	34.73	<0.0001	
LAI Acacia koa	319.47	1	319.47	34.73	<0.0001	
Error	239.18	26	9.2			
Total	558.66	27				
Coefficients of correlation						
Pearson correlation						
Variable(1)	Variable(2)	n	Pearson	p-value		
Crude Protein % Kikuyu	LAI Acacia koa	28	0.76	<0.0001		

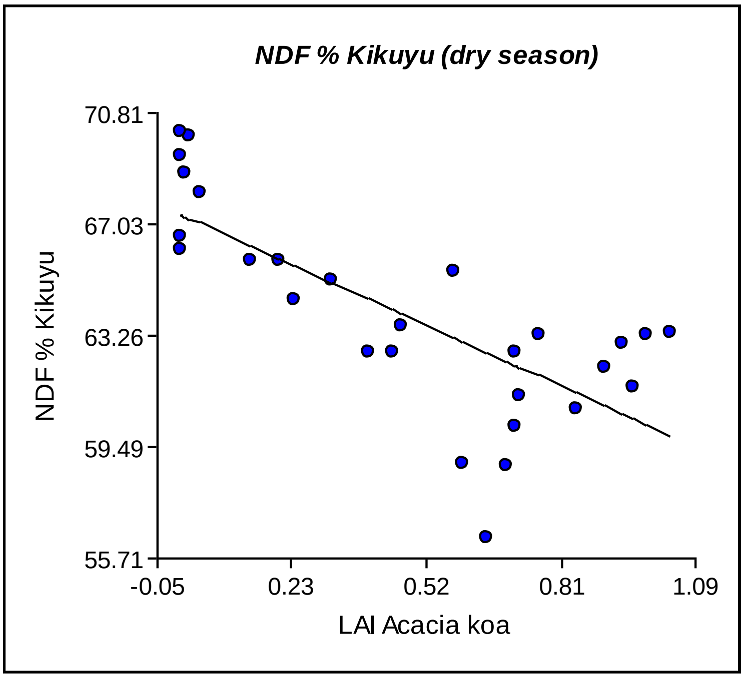

Figure A.5. Dry-season NDF (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.9. Dry-season NDF (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
NDF % Kikuyu	28	0.56	0.54	6.36	131.15	135.15

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	67.36	0.75	65.82	68.9	90.1	<0.0001
LAI Acacia koa	-7.19	1.26	-9.78	-4.61	-5.72	<0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	180.01	1	180.01	32.69	<0.0001
LAI Acacia koa	180.01	1	180.01	32.69	<0.0001
Error	143.16	26	5.51		
Total	323.17	27			

Correlation coefficients				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
NDF % Kikuyu	LAI Acacia koa	28	-0.75	<0.0001

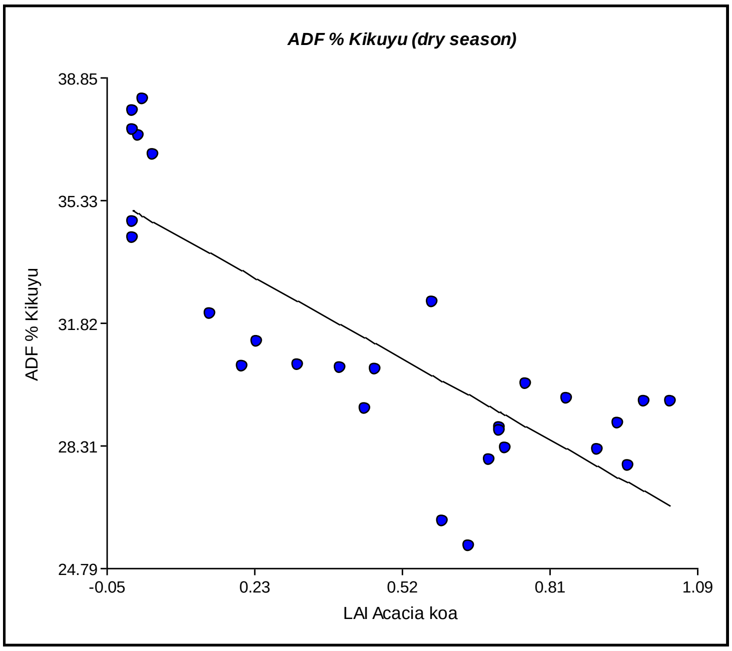

Figure A.6. Dry-season ADF (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.10. Dry-season ADF (%) in kikuyu, in relation to (LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
ADF % Kikuyu	28	0.65	0.64	5.46	126.7	130.7
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	35.04	0.69	33.62	36.46	50.75	<0.0001
LAI Acacia koa	-8.13	1.16	-10.51	-5.74	-6.99	<0.0001
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	229.81	1	229.81	48.92	<0.0001	
LAI Acacia koa	229.81	1	229.81	48.92	<0.0001	
Error	122.13	26	4.7			
Total	351.93	27				
Correlation coefficients						
Pearson correlation						
Variable(1)	Variable(2)	n	Pearson	p-value		
ADF % Kikuyu	LAI Acacia koa	28	-0.81	<0.0001		

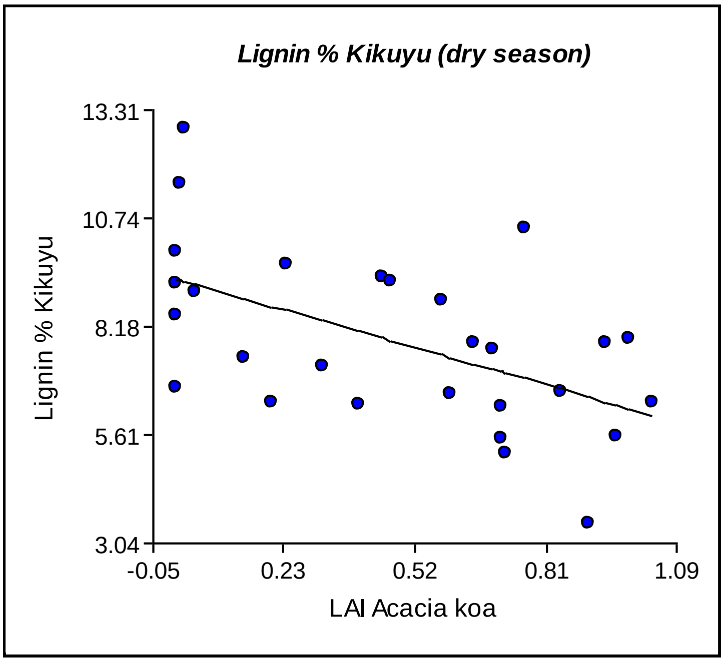

Figure A.7. Dry-season lignin (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.11. Dry-season lignin (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Lignin % Kikuyu	28	0.3	0.27	3.57	114.6	118.59

Coefficients of regression						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	9.3	0.56	8.16	10.44	16.72	<0.0001
LAI Acacia koa	-3.1	0.94	-5.02	-1.18	-3.31	0.0027

ANOVA					
F.V.	SC	gl	CM	F	p-value
Model	33.44	1	33.44	10.97	0.0027
LAI Acacia koa	33.44	1	33.44	10.97	0.0027
Error	79.27	26	3.05		
Total	112.71	27			

Coefficients of correlation				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
Lignin % Kikuyu	AI Acacia koa	28	-0.54	0.0027

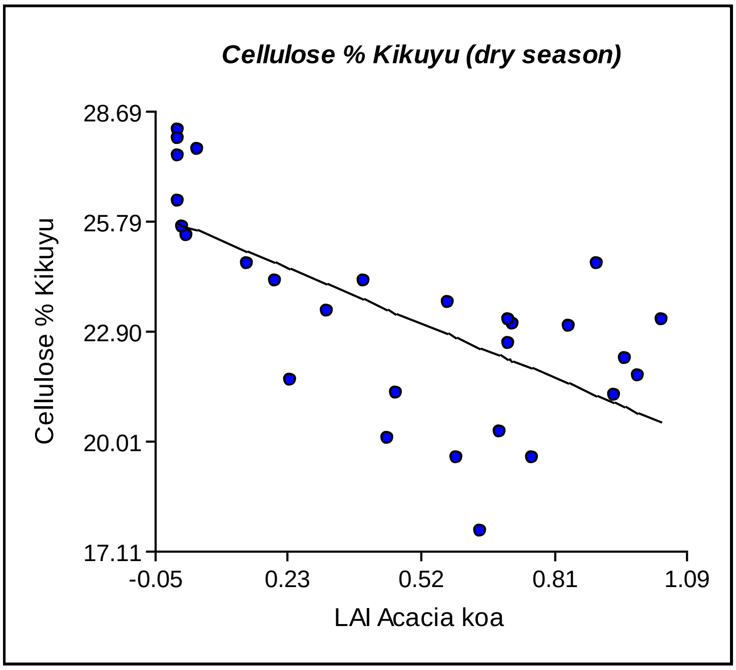

Figure A.8. Dry-season cellulose (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.12. Dry-season cellulose (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Cellulose % Kikuyu	28	0.44	0.41	5.03	124.77	128.77
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	25.74	0.67	24.37	27.12	38.59	<0.0001
LAI Acacia koa	-5.03	1.12	-7.34	-2.73	-4.48	0.0001
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Model	88.15	1	88.15	20.11	0.0001	
LAI Acacia koa	88.15	1	88.15	20.11	0.0001	
Error	113.99	26	4.38			
Total	202.14	27				

Coefficients of correlation				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
Cellulose % Kikuyu	LAI Acacia koa	28	-0.66	0.0001

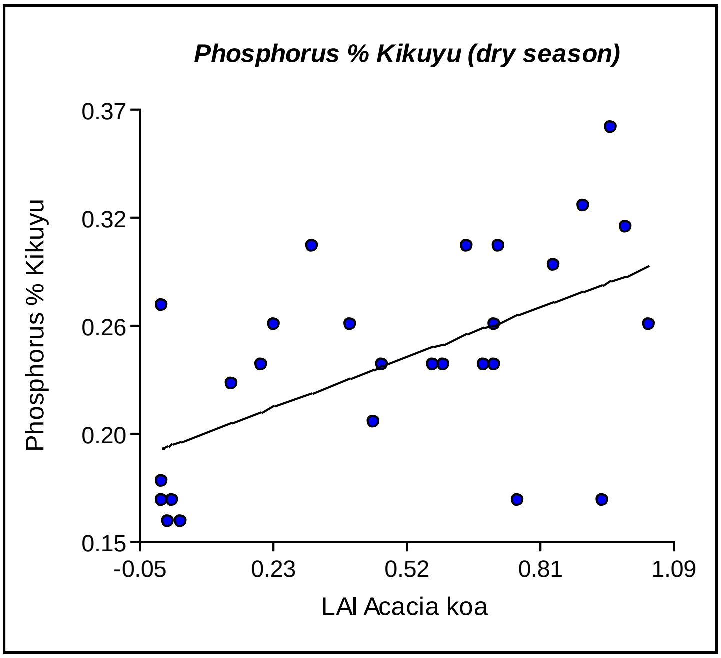

Figure A.9. Dry-season phosphorus (%) in kikuyu, in relation to LAI of *A. koa.*

Table A.13. Statistical analysis for relationship between LAI of *A. koa* and dry-season phosphorus (%) in kikuyu. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Phosphorus % Kikuyu	28	0.33	0.3	2.50E-03	-88.5	-84.5

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.2	0.01	0.17	0.23	13.35	<0.0001
LAI Acacia koa	0.09	0.02	0.04	0.14	3.56	0.0015

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	0.03	1	0.03	12.66	0.0015
LAI Acacia koa	0.03	1	0.03	12.66	0.0015
Error	0.06	26	2.20E-03		
Total	0.08	27			

Coefficients of correlation				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
Phosphorus % Kikuyu	LAI Acacia koa	28	0.57	0.0015

Wet season forage analysis results

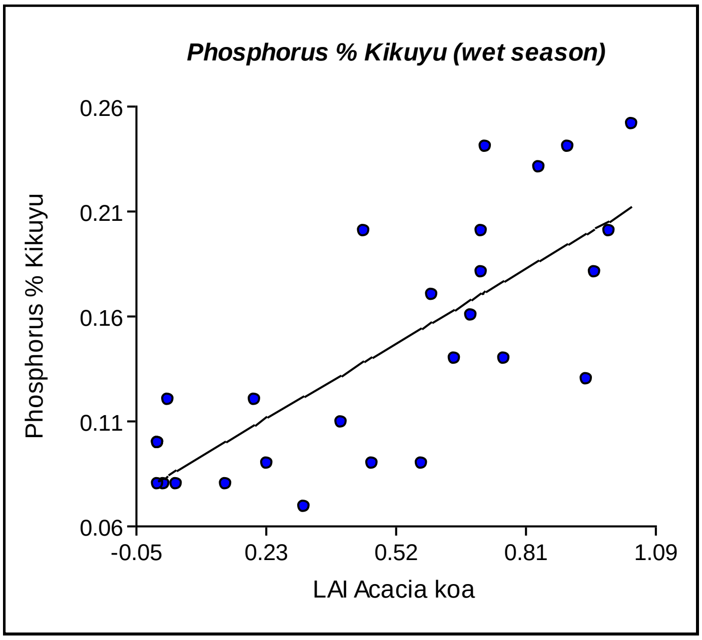

Figure A.10. Wet-season phosphorus (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.14. Wet-season phosphorus (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Phosphorus % Kikuyu	28	0.6	0.58	1.60E-03	-101.31	-97.31
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.08	0.01	0.06	0.11	7.01	<0.0001
LAI Acacia koa	0.12	0.02	0.08	0.16	6.25	<0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	0.05	1	0.05	39.04	<0.0001
LAI Acacia koa	0.05	1	0.05	39.04	<0.0001
Error	0.04	26	1.40E-03		
Total	0.09	27			

Correlation coefficients				
Pearson correlation				
Variable(1)	Variable(2)	n	Pearson	p-value
Phosphorus % Kikuyu	LAI Acacia koa	28	0.77	<0.0001

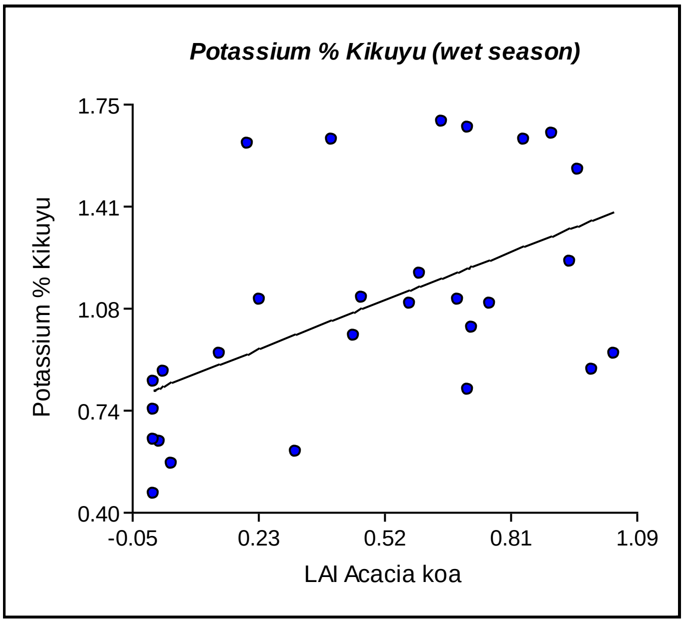

Figure A.11. Wet-season potassium (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.15. Wet-season potassium (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Potassium % Kikuyu	28	0.29	0.26	0.12	20.53	24.53
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.81	0.1	0.59	1.02	7.76	<0.0001
LAI Acacia koa	0.57	0.17	0.21	0.93	3.25	0.0032
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	1.12	1	1.12	10.59	0.0032	
LAI Acacia koa	1.12	1	1.12	10.59	0.0032	
Error	2.75	26	0.11			
Total	3.88	27				

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
Potassium % Kikuyu	LAI Acacia koa	28	0.54	0.0032

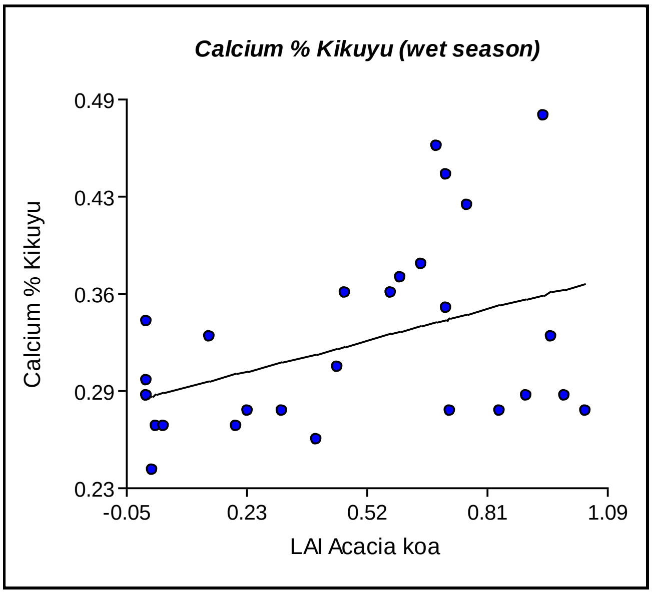

Figure A.12. Wet-season calcium (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.16. Wet-season calcium (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Calcium % Kikuyu	28	0.18	0.14	4.10E-03	-75.24	-71.24
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.29	0.02	0.25	0.33	15.43	<0.0001
LAI Acacia koa	0.07	0.03	0.01	0.14	2.36	0.0263
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	0.02	1	0.02	5.55	0.0263	
LAI Acacia koa	0.02	1	0.02	5.55	0.0263	
Error	0.09	26	3.50E-03			
Total	0.11	27				
Coefficients of correlation						
Correlación de Pearson						
Variable(1)	Variable(2)	n	Pearson	p-value		
Calcium % Kikuyu	LAI Acacia koa	28	0.42	0.0263		

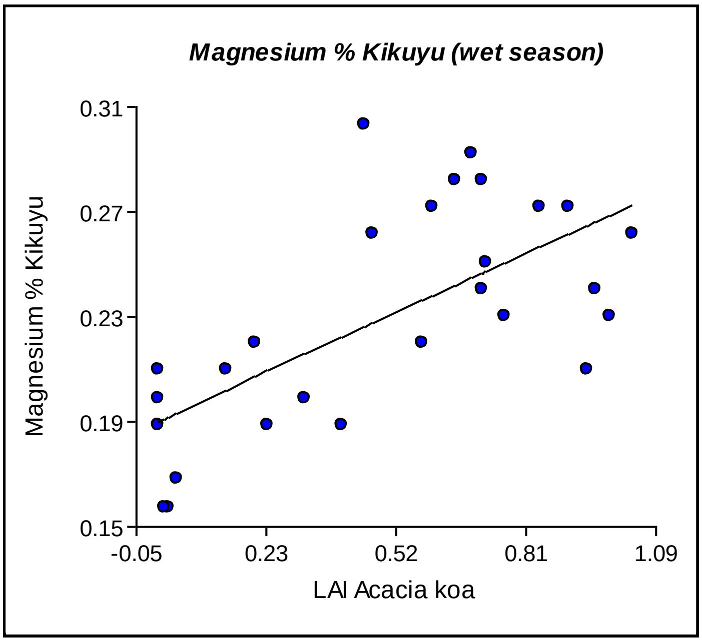

Figure A.13. Wet-season magnesium (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.17. Wet-season magnesium (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Magnesium % Kikuyu	28	0.46	0.44	1.00E-03	-113.02	-109.02

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	0.19	0.01	0.17	0.21	20.07	<0.0001
LAI Acacia koa	0.08	0.02	0.04	0.11	4.75	0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	0.02	1	0.02	22.52	0.0001
LAI Acacia koa	0.02	1	0.02	22.52	0.0001
Error	0.02	26	9.00E-04		
Total	0.04	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
Magnesium % Kikuyu	LAI Acacia koa	28	0.68	0.0001

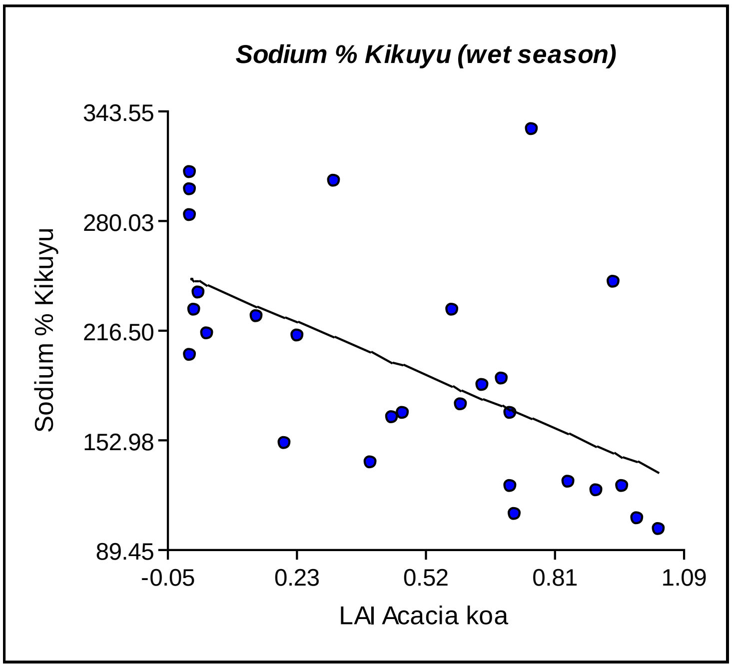

Figure A.14. Wet-season sodium (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.18. Wet-season sodium (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Sodium % Kikuyu	28	0.33	0.31	3549.66	308.35	312.35
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	246.76	17.7	210.38	283.14	13.94	<0.0001
LAI Acacia koa	-107.7	29.77	-168.9	-46.5	-3.62	0.0013
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	40377.3	1	40377.3	13.09	0.0013	
LAI Acacia koa	40377.3	1	40377.3	13.09	0.0013	
Error	80229.41	26	3085.75			
Total	120606.71	27				
Coefficients of correlation						
Pearson correlation						
Variable(1)	Variable(2)	n	Pearson	p-value		
Sodium % Kikuyu	LAI Acacia koa	28	-0.58	0.0013		

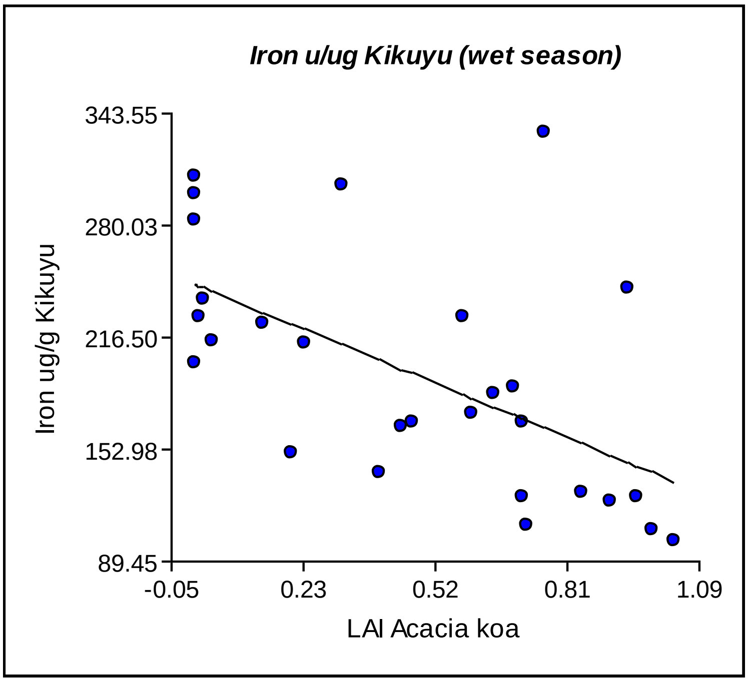

Figure A.15. Wet-season iron (u/ug) in kikuyu, in relation to LAI of *A. koa*.

Table A.19. Wet-season iron (u/ug) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Iron ug/g Kikuyu	28	0.33	0.31	3549.66	308.35	312.35

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	246.76	17.7	210.38	283.14	13.94	<0.0001
LAI Acacia koa	-107.7	29.77	-168.9	-46.5	-3.62	0.0013

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	40377.3	1	40377.3	13.09	0.0013
LAI Acacia koa	40377.3	1	40377.3	13.09	0.0013
Error	80229.41	26	3085.75		
Total	120606.71	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
Iron ug/g Kikuyu	LAI Acacia koa	28	-0.58	0.0013

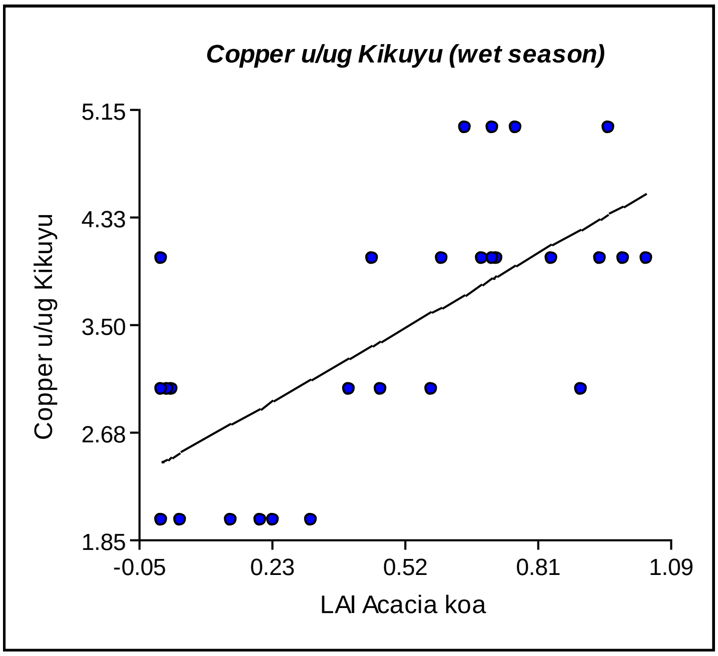

Figure A.16. Wet-season copper (u/ug) in kikuyu, in relation to LAI of *A. koa*.

Table A.20. Wet-season copper (u/ug) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Copper u/ug Kikuyu	28	0.48	0.46	0.67	67.87	71.87

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	2.44	0.24	1.95	2.94	10.11	<0.0001
LAI Acacia koa	1.99	0.41	1.15	2.82	4.89	<0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	13.74	1	13.74	23.91	<0.0001
LAI Acacia koa	13.74	1	13.74	23.91	<0.0001
Error	14.94	26	0.57		
Total	28.68	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
Copper u/ug Kikuyu	LAI Acacia koa	28	0.69	<0.0001

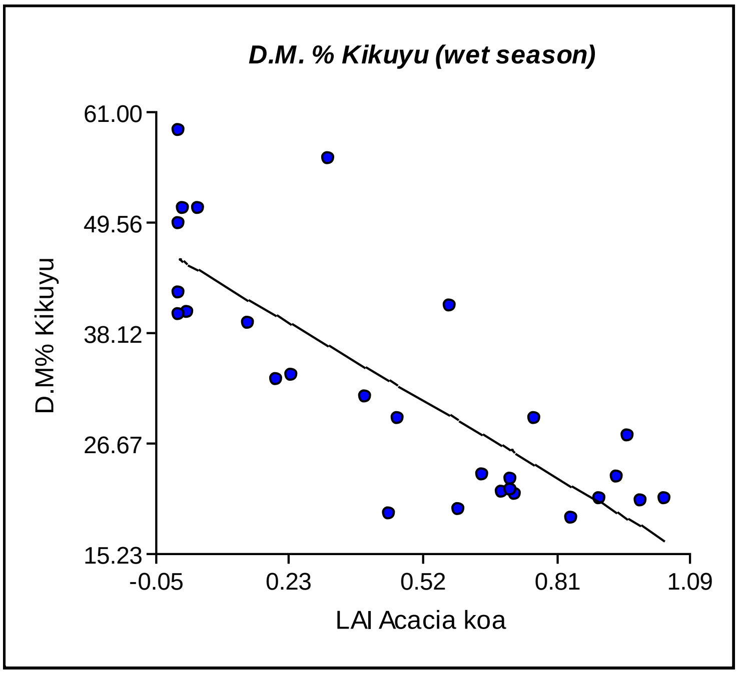

Figure A.17. Wet-season dry matter (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.21. Wet-season dry matter (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
D.M% Kikuyu	28	0.65	0.64	62.95	195.79	199.79
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	45.7	2.37	40.83	50.57	19.27	<0.0001
LAI Acacia koa	-27.9	3.99	-36.1	-19.7	-6.99	<0.0001
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	2709.78	1	2709.78	48.92	<0.0001	
LAI Acacia koa	2709.78	1	2709.78	48.92	<0.0001	
Error	1440.26	26	55.39			
Total	4150.04	27				
Coefficients of correlation						
Correlación de Pearson						
Variable(1)	Variable(2)	n	Pearson	p-value		
D.M% Kikuyu	LAI Acacia koa	28	-0.81	<0.0001		

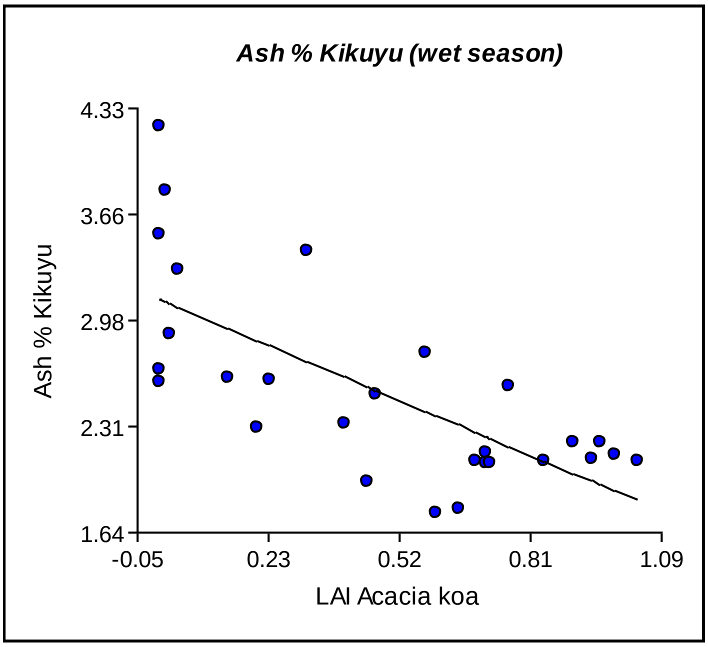

Figure A.18. Wet-season ash (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.22. Wet-season ash (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Ash % Kikuyu	28	0.5	0.49	0.23	37.84	41.84
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	3.11	0.14	2.82	3.4	22.05	<0.0001
LAI Acacia koa	-1.22	0.24	-1.71	-0.73	-5.15	<0.0001
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	5.21	1	5.21	26.48	<0.0001	
LAI Acacia koa	5.21	1	5.21	26.48	<0.0001	
Error	5.11	26	0.2			
Total	10.32	27				
Coefficients of correlation						
Correlación de Pearson						
Variable(1)	Variable(2)	n	Pearson	p-value		
Ash % Kikuyu	LAI Acacia koa	28	-0.71	<0.0001		

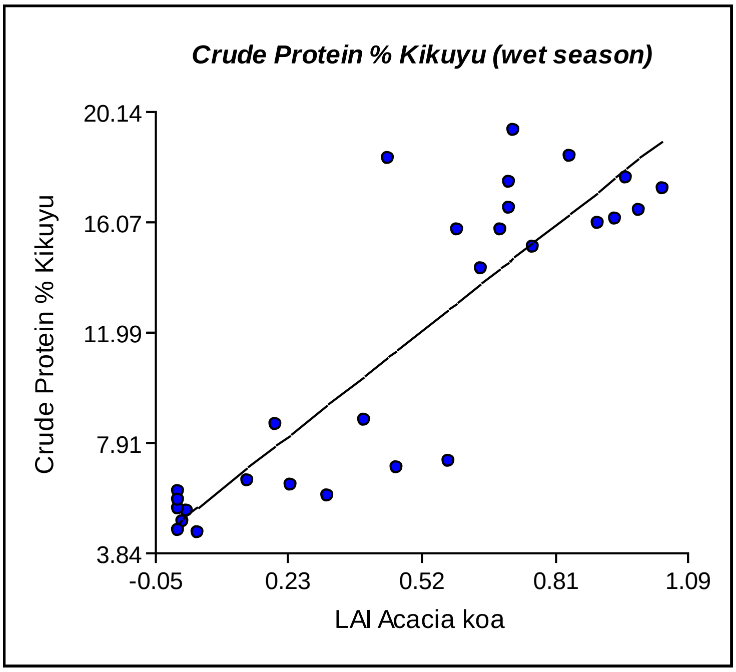

Figure A.19. Wet-season crude protein (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.23. Wet-season crude protein (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Crude Protein % Kikuyu	28	0.78	0.77	7.84	138.31	142.31

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	4.98	0.85	3.23	6.72	5.86	<0.0001
LAI Acacia koa	13.6	1.43	10.67	16.54	9.52	<0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	644.2	1	644.2	90.58	<0.0001
LAI Acacia koa	644.2	1	644.2	90.58	<0.0001
Error	184.91	26	7.11		
Total	829.1	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
Crude Protein % Kikuyu	LAI Acacia koa	28	0.88	<0.0001

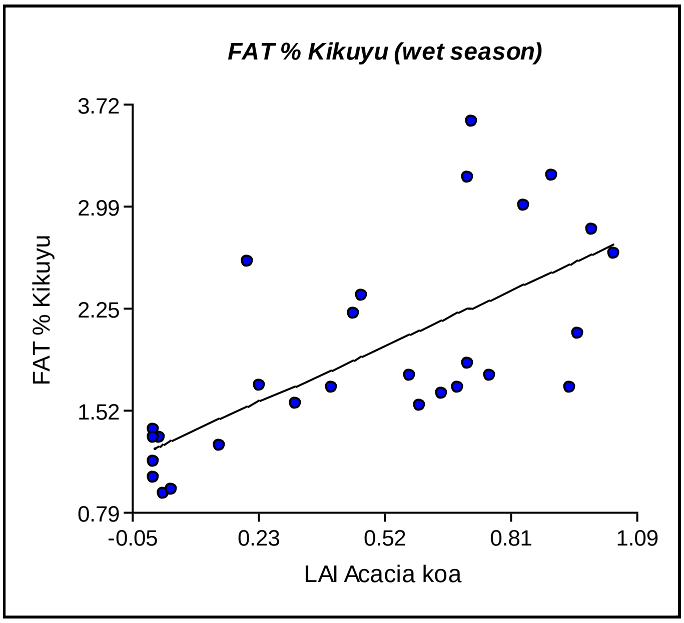

Figure A.20. Wet-season fat (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.24. Wet-season fat (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Fat % Kikuyu	28	0.47	0.45	0.34	49.64	53.64

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	1.25	0.17	0.89	1.61	7.16	<0.0001
LAI Acacia koa	1.41	0.29	0.8	2.01	4.79	0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	6.89	1	6.89	22.98	0.0001
LAI Acacia koa	6.89	1	6.89	22.98	0.0001
Error	7.79	26	0.3		
Total	14.68	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
Fat % Kikuyu	LAI Acacia koa	28	0.68	0.0001

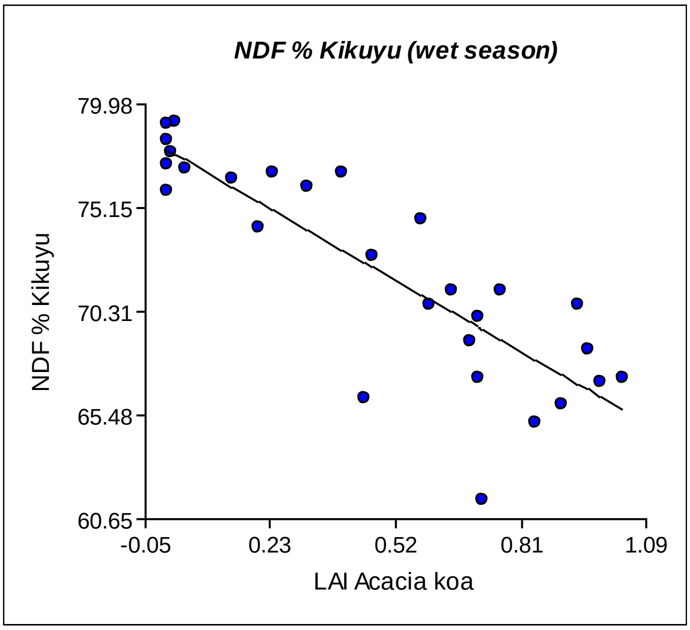

Figure A.21. Wet-season NDF (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.25. Wet-season NDF (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
NDF % Kikuyu	28	0.72	0.7	8.1	138.73	142.72

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	77.84	0.86	76.08	79.6	90.94	<0.0001
LAI Acacia koa	-11.64	1.44	-14.6	-8.68	-8.08	<0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	471.41	1	471.41	65.32	<0.0001
LAI Acacia koa	471.41	1	471.41	65.32	<0.0001
Error	187.65	26	7.22		
Total	659.06	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
NDF % Kikuyu	LAI Acacia koa	28	-0.85	<0.0001

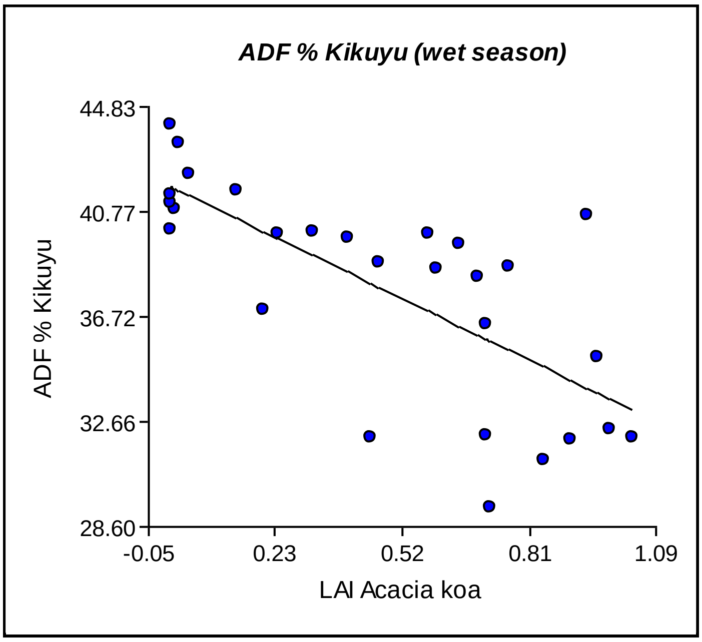

Figure A.22. Wet-season ADF (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.26. Wet-season ADF (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
ADF % Kikuyu	28	0.52	0.5	9.81	143.57	147.56

Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	41.75	0.93	39.83	43.67	44.74	<0.0001
LAI Acacia koa	-8.3	1.57	-11.53	-5.08	-5.29	<0.0001

ANOVA					
F.V.	SC	gl	CM	F	p-value
Modelo.	240.03	1	240.03	27.98	<0.0001
LAI Acacia koa	240.03	1	240.03	27.98	<0.0001
Error	223.06	26	8.58		
Total	463.08	27			

Coefficients of correlation				
Correlación de Pearson				
Variable(1)	Variable(2)	n	Pearson	p-value
ADF % Kikuyu	LAI Acacia koa	28	-0.72	<0.0001

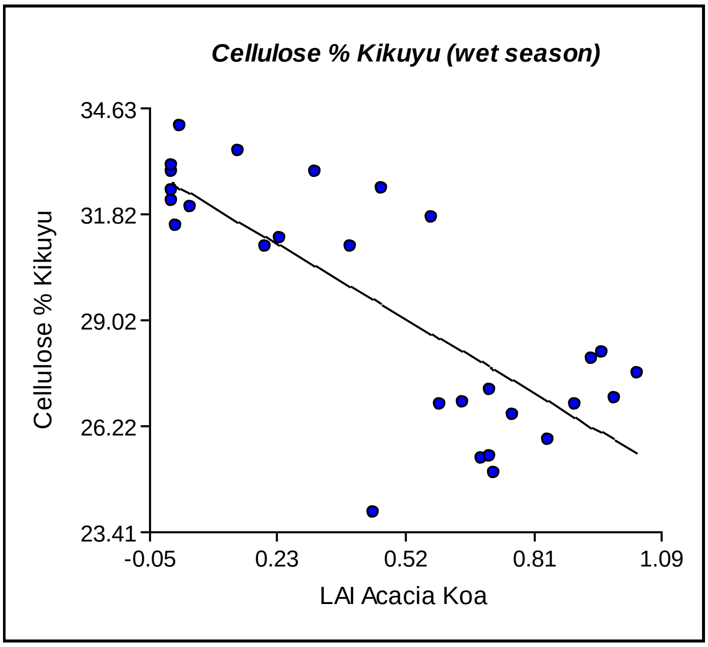

Figure A.23. Wet-season cellulose (%) in kikuyu, in relation to LAI of *A. koa*.

Table A.27. Wet-season cellulose (%) in kikuyu, in relation to LAI of *A. koa*. P-values less than .05 suggest a significant difference.

Regression analysis						
Variable	N	R^2	R^2 Aj	ECMP	AIC	BIC
Cellulose % Kikuyu	28	0.61	0.59	4.57	122.8	126.79
Regression coefficients						
Coef	Est.	E.E.	LI(95%)	LS(95%)	T	p-value
const	32.64	0.64	31.31	33.96	50.68	<0.0001
LAI Acacia Koa	-6.86	1.08	-9.09	-4.63	-6.33	<0.0001
ANOVA						
F.V.	SC	gl	CM	F	p-value	
Modelo.	163.79	1	163.79	40.09	<0.0001	
LAI Acacia Koa	163.79	1	163.79	40.09	<0.0001	
Error	106.23	26	4.09			
Total	270.02	27				
Coefficients of correlation						
Pearson correlation						
Variable(1)	Variable(2)	n	Pearson	p-value		
Cellulose % Kikuyu	LAI Acacia Koa	28	-0.78	<0.0001		