Optimal land allocation for Hawaiian agriculture using an entropy-based approach

by

Jonathan Takao Kaneshiro

B.S.E. Civil Engineering, Loyola Marymount University (2016)

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

Masters of Engineering in Environmental Engineering

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

For over 50 years in The State of Hawai'i, the issues of food self sufficiency and environmental resource protection have been called for, but not necessarily addressed in a quantitative manner. These concerns have been key priorities in The State of Hawai'i Constitution, Hawai'i 2050 Sustainability Plan, Hawai'i County Development Plan and various Community Development Plans. As Hawaiian agriculture transitions from industrial mono-cropping plantation landscapes to small stakeholder farms, it is more important than ever to challenge these issues in the most efficient and sustainable way that is conscious of both environmental resources and resident values. This thesis aims to quantitatively allocate land and environmental resources using a representative entropy-based optimization model, which is formulated to maintain biodiversity while maximizing food self-sufficiency. Rigorous methods to quantify biophysical, water and land resources are implemented to ensure a robust output of optimal cropping areas on a pixel basis. Tradeoff curves are generated comparing fractions of land needed for agricultural expansion, self-sufficient population in fruits and vegetables and total entropy of Hawai'i Island. Results show that Hawai'i Island could sustain up to 6M people in fruits and vegetables, while maintaining the highest spatial heterogeneity and biodiversity. The high populations, however, should be assessed with regard to the cropping land expansions and changes in landscape, as these tradeoffs may outweigh the benefits.

Thesis Supervisor: Dennis McLaughlin
Title: H.M. King Bhumibol Professor of Water Resource Management

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Most importantly, thank you Mom, Dad, Matt and Landon for your unconditional love and support. I know that, in whatever I do, you all will be there to guide and encourage me.

I owe all my accomplishments to my family and could not be more grateful. With this, I dedicate my thesis to them.

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Chapter 1

Introduction

1.1 Overview

The issue of food self-sufficiency in The State of Hawai'i is a paramount topic, which among many others, affects the political, cultural, public, economic and environmental domains. The Food and Agriculture Organization of the United Nations (FAO) defines food self-sufficiency as "the extent to which a country can satisfy its food needs from its own domestic production" (Thomson and Metz, 1999). Although food self-sufficiency is usually a concern for developing countries, Hawai'i is a particular exception because of its vulnerability to external global shifts and already significantly high dependence on foreign commodities.

Various sources have reached a consistent range of Hawai'i's dependence on food imports to be between 80% and 90%. In other words, only about 15% of the food on an average plate is locally produced. Although market constraints and global trade make 100% food self-sufficiency infeasible, increasing self-sufficiency in certain categories of crops is important to explore and evaluate.

1.2 Motivation

This thesis has been developed in response to the multiple calls to action from the state level to the individual counties and communities. In a 1978 amendment, The Hawai'i

State Constitution Article XI urged for an increase in "agricultural self-sufficiency" that promotes availability and diversity in addition to natural resource conservation (HSC, 1978).

Furthermore, in January 2008, The State of Hawai'i introduced The Hawai'i 2050 Suitability Plan (HI2050), the State's first long-term plan in 30 years. One of the major goals introduced in HI2050 is to "develop a more diverse and resilient economy" as well as "conserve agricultural, open space and conservation lands and resources." The proposed strategy calls for an "increase [in] production and consumption of local foods and products, particularly agricultural products" and to "encourage 'smart growth' concepts in land use and community planning." These intentions require a coupling of both environmental resource management and allocation, two important factors that are considered in this study.

Counties of Hawai'i have also addressed the food self-sufficiency problem. In 2010, Hawai'i County drafted their own agriculture development plan titled *The 2010 County of Hawai'i Agriculture Development Plan* (HCDP). One of the main recommended goals is to "expand Hawai'i Island food production so that 30% of its residents' demand for food can be supplied by local producers by 2020." Various communities have also emphasized local agriculture, natural resource protection and self-sufficiency though Community Development Plans (CPD). North Kohala's CPD has a goal to "produce 50% of the food it consumes" (The Kohala Center, 2010).

With the numerous development plans and goals to increase food self-sufficiency while promoting both environmental and economic health, this thesis sets a platform to assess the current and potential agricultural condition of Hawai'i. We focus on Hawai'i Island because of its significantly larger area and relatively open land for crop expansion. The United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) estimated Hawai'i Island to hold over 30% of the total agricultural market value for the State. In the most recent 2012 USDA NASS Census, Hawai'i Island contributed 37.3% to the State agricultural market value. Additionally, the Rocky Mountain Institute reported that Hawai'i Island holds 63% of the agricultural land in the State (Page et al., 2007). These statistics, in addition to the widely variable biophysical resources on Hawai'i Island hint at the possibility of expanding crop-based agriculture to increase food self-sufficiency.

The concern for supporting local agriculture, upholding ecological health and reducing foreign dependence has grown in the last 30 years. Today, Hawai'i is in a transitional period from large mono-cropping plantations to smaller diversified farms, making it more important than ever to evaluate the current and potential state of Hawaiian agriculture. In order to do this, we have developed a constrained optimization model that allocates land and natural resources for crop production, while maximizing spatial heterogeneity. This method allows policymakers, community leaders and farmers to evaluate tradeoffs between the number of self-sufficient people, the area of land needed for agricultural expansion and the level of biodiversity.

Although there have been studies and assessments of Hawaiian food self-sufficiency, none have approached this problem quantitatively to the extent of evaluating biophysical crop suitability and ecological heterogeneity in tandem with land and water balance constraints.

1.3 Reasons For Self-Sufficiency

Food self-sufficiency is important in every civilization and must remain a top priority in order for a society to prosper. With increased food self-sufficiency comes heightened security relating to environmental, economic, social and health issues. Highlighted examples include scenarios in which tourism declines, fuel shortages occur or development/urbanization spreads (Page et al., 2007).

Food self-sufficiency is particularly important for Hawai'i because of its isolation and history. The following subsections describe how the cultural and agricultural histories (often the same) of Hawai'i have become the underlying motivations for biodiverse food self-sufficient systems.

1.3.1 Agricultural History

Discussed further in Chapter 3, the shift from a widely diversified cropping system to a mono- and cash-crop structure altered both the economic state and ecological landscape of Hawai'i. Presently, this structure is again transforming after a century of widespread plantations, making it crucial to execute careful decisions based on past observations. Increasing food self-sufficiency and cash crop export revenue are not mutually exclusive. However, it is implied that they are inversely related, making a concentrated mono-cropping society unfavorable for food self-sufficiency.

Although temporarily profitable, the increase in mono-cropping agricultural systems has proven to be economically short-lived, ecologically harmful and considerably unstable for Hawai'i. Evidence for this is widely documented from the history of the pervasive sugar, pineapple and papaya farms. The rise and fall, particularly of the sugar and pineapple plantations, prove the sensitivity in basing an agricultural system on cash-crops. These types of arrangements are highly dependent on global markets and do not hold stable during times of expansion or national/global uncertainty. Volatility was seen during World War II, when pineapple and sugar plantations moved to foreign countries for more land and cheaper labor (Batholomew et al., 2012).

Additionally, in the late 20^{th} century, the Papaya Ringspot Virus (PRV), which was a deadly disease with no chemical cure (Nishina et al., 1989), threatened Hawai'i's papaya industry in the Puna region of Hawai'i Island, which grew 95% of the papaya for the State. The only solution at that time was to introduce transgenic papaya strains that were resistant to PRV (Gonsalves et al., 2004). Luckily, the genetically modified plants were able to restore the papaya industry, which could have easily fallen if the strains did not work. Although the economic state of Hawai'i has recovered since these failures, the understated ecological conditions remain at large.

Recently, Cutler et al. (2016) detected high concentrations of toxic arsenic on old Hawai'i Island plantation areas due to the excessive use of herbicide. This finding raises concern of pesticide usage as it poses a threat to both human (e.g. Alam, 1994; Repetto and Baliga, 1996) and environmental health. The extensive use of pesticides correlate with mono-cropping agriculture, as more pests accumulate with lower competition and diversity.

Biodiverse systems have proven to regulate pests in many ways and reduce the use of chemical pesticides by supporting natural enemies (e.g. Nentwig et al., 1998), integrating "decoy" plants (Mensah and Kahn, 1997) and promoting poorly understood supportive mechanisms that occur between plants and microorganisms. Studies have shown that an increase in biodiversity also increases crop yields because of synergistic symbiotic processes between varying biota (Vandermeer, 1990; Frison et al., 2011; Weigelt et al., 2009; Tilman et al., 2001). For example, one of many studies have reported that when intercropped, chickpea can mobilize organic phosphorus, which leads to higher yields in maize (Li et al., 2004).

In all, the mono-cropping agricultural history of Hawai'i has proven unstable and harmful to both the economy and environment. During this time of transition, it is critical to learn from the past and move forward accordingly. Many studies have concluded that increasing biodiversity both on the macro- and micro-levels would be beneficial for accentuating crop production, reducing pesticide usage, encouraging natural enemies, lessening soil degradation and providing a robust strategy during times of economic or environmental instability (e.g. Thies and Tscharnkte, 1999; Gurr et al., 2003). With this in mind, crop allocation for food self-sufficiency should be diversified in a manner that maintains maximum biodiversity and spatial heterogeneity.

1.3.2 Cultural History

Hawai'i is an unique place with rich cultural values and history, where residents are adamant about remaining as sustainable and independent as possible. This fact cannot be ignored. These ideologies manifest from Hawaiian agricultural history, when the Hawaiian people had been 100% food self-sufficient before contact with Westerners in the late 18^{th} century. It was only after this contact when food self-sufficiency decreased due to foreign trade exposure. At its height, Hawai'i Island completely sustained 100,000 to 150,000 people (Schmitt, 1971), compared to the

198,000 people living on Hawai'i Island today (USCB, 2016).

In addition to ecological benefits, incorporating biodiversity into agricultural land-use planning and economic models would also align with resident desires and opinions (Saunders and Walker, 1998). This includes the support for wildlife conservation, general aesthetics and recreational benefits for the society to enjoy (Gurr et al., 2003). In a survey done in 2007, 61.3% of Hawai'i residents were willing to pay higher taxes to protect the environment and 68.1% believed the government should conserve cultural sites above economic development (HI2050). These types of statistics show that the majority of Hawai'i residents believe in keeping Hawai'i as diverse as possible and in protecting the natural landscape from industrial farming and commercial activity.

1.4 Why Is Self-Sufficiency Not Happening?

To address this question, we developed a preliminary optimization model to evaluate the tradeoff between food self-sufficiency and export revenue. Results indicated that Hawai'i Island could multiply its export revenue from coffee and macadamia almost 10-fold, which could bring in hundreds of millions of dollars[1] from agricultural production. Hawai'i has not produced near this level, meaning that there is a limiting factor that is constraining export revenue and food self-sufficiency.

The optimization model constructed industrial-sized coffee and macadamia farms that produced massive quantities of product for export. This scenario would demand immense capital and outside investment, which would mirror the onset of the Plantation Era. Substantial plots of mono-cropped lands would be closed to local residents and environmental risks would surely increase. Although the preliminary results seemed exceptional, the underlying costs outweighed the benefits, and to some extent, were unrealistic.

For Hawai'i, it is necessary to increase food production while allocating land resources to maintain open lands and diversity. As a result, we have developed a more realistic optimization model, which integrates entropy as a metric for ecological bio-

[1]Market demand and supply functions were not included in this model.

diversity and spatial heterogeneity. This new type of evaluation increases agricultural production while maximizing diversity, moving away from mono-cropping and environmentally harmful systems. The optimized results favor small stakeholder farmers, native vegetation and local resident ideologies, effectively penalizing for industrial farms and large privatized lands.

1.5 Thesis Outline

This thesis has been formulated to quantitatively answer some of the floating food self-sufficiency and environmental initiatives that have been proposed, but not addressed. It is important to note that food self-sufficiency, in the context of this thesis, is self-sufficiency in fruits and vegetables. Protein, carbohydrates, fats, etc... are not considered due to limitations in data and time.

First, we review the physical status and setting of Hawai'i and Hawai'i Island. Understanding the extremely diverse climates and soils in addition to the natural resources of Hawai'i Island is crucial in assessing the potential for crop expansion and allocation.

Next, a brief history of Hawaiian agriculture, pertaining to cash and food crops, is expanded upon to emphasize how dominant and important agriculture has been to The State of Hawai'i and to provide an understanding of how dynamic this structure was and is still today. This section will also evaluate the current state of self-sufficiency with respect to historic trends.

Following these overview sections are the optimization models, discussions and results. The first part (Chapter 4) describes the processes to estimate zonal crop and non-crop water requirements for Hawai'i Island via least-squares optimization. This preliminary process is necessary to acquire representative water requirement data, which are required in the entropy-based optimization model in Chapter 5.

Finally, the entropy-based optimization discussion and results are presented (Chapter 5), showing the tradeoff between population self-sufficient and spatial heterogeneity/biodiversity for a given amount of agricultural land. This chapter ends with suggestions for further research and interpretations of the optimization model's output.

Chapter 2

Hawai'i and Hawai'i Island

2.1 The Hawaiian-Emperor Seamount Chain

The Hawaiian-Emperor seamount chain (Figure 2-1) consists of the 8 major Hawaiian Islands as well as the Emperor Seamounts northwest of the Hawaiian archipelago. Together, the chain spans 6000km (3700mi) from Hawai'i Island to the Aleutian Trench near Alaska and consists of islands, atolls, reefs and seamounts. Kure Atoll (considered the most northeast atoll) to Hawai'i Island is approximately 2400km (1500mi).

The origin of the Hawaiian Islands remained a mystery until the 1960s, when scientists were able to confirm geologist J. Tuzo Wilson's 1963 hypothesis of the hot-spot origin and theory of plate tectonics (Tuzo, 1963) through potassium-argon radioactive dating (Olson, 1998). The dating validated the movement of the oceanic crust and relative ages of the Islands, enabling scientists to infer reasons for the causes of diverse soils and landscapes in a linear chain-like spatial extent.

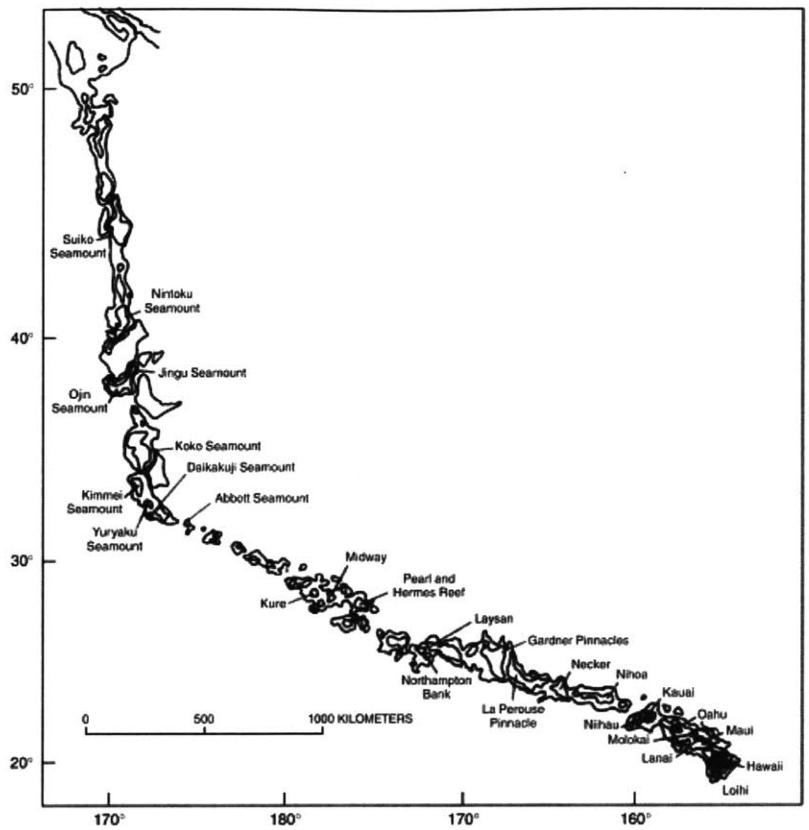

Figure 2-1: The Hawaiian-Emperor Seamount Chain. Source: Olson, 1998

2.2 Physical Composition and Climatic Setting of the Hawaiian Islands

The Hawaiian Islands (Figure 2-2) are 4000km (2500mi) from the nearest continent and remains the most isolated archipelago in the world (HCDP, 2010). With an estimated area of 16700km^2 (6450mi^2), 8 major islands, 124 smaller landmasses and a 2400km (1500mi) span (Juvic and Juvic, 1988), its age, topographic layout, oceanic setting and volcanic parent materials induce considerable climatic, geological, soil and ecological variability. Within 500km (300mi), mountains range from 4250m (14000ft) to 1500m (4900ft) and ages vary from 0.5My (M = million) to over 5My old (Olson, 1998).

Juvik et al. (1978) discovered and observed 10 out of the 14 Köppen Climate Classifications on the Hawaiian Islands. These climates include humid, arid, semi-arid, temperate and periglacial. The complex systems of valleys, peaks and ridges produce localized climates that range from sub-arctic high mountain terrain on Hawai'i Island to Oahu's and Maui's dry interior lowlands. Annual precipitation ranges from 200mm/yr (8in/yr) on the summit of Mauna Kea to over 10000mm/yr (400in/yr) on Maui and Kaua'i (Giambelluca et al., 2013). Although temperature is not as spatially variable because of oceanic moderation, temperature gradients range from -11°C (12°F) on mountain tops to 38°C (100°F) in low lying valleys (Price, 1983).

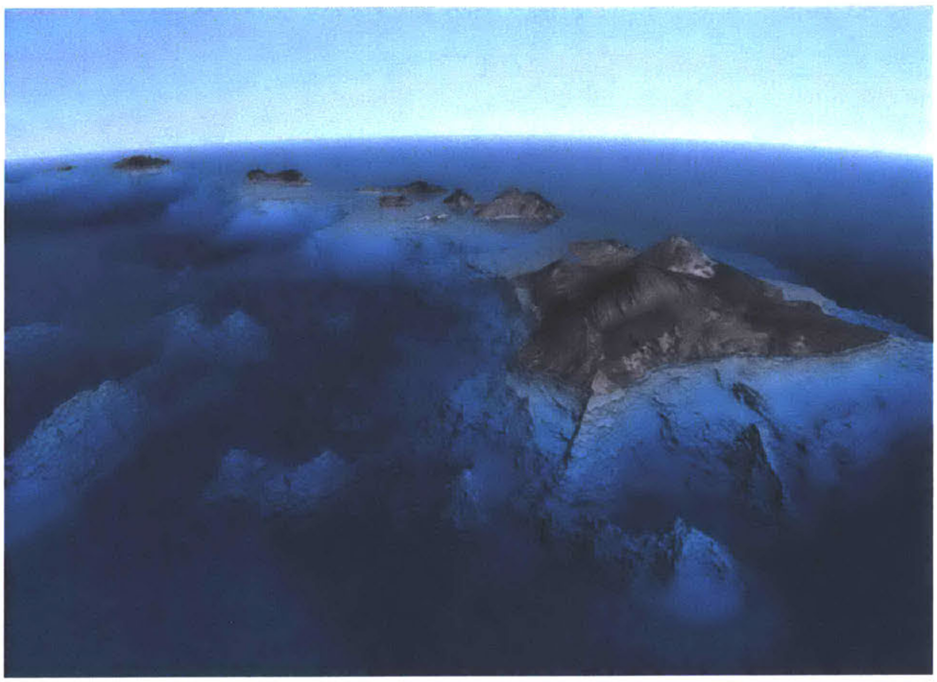

Figure 2-2: 3D Rendering of the Hawaiian Islands. Source: http://www.soest.hawaii.edu/

2.2.1 Focus on Hawai'i Island

Hawai'i Island is approximately 10400km^2 (4028mi^2) and is home to four active volcanoes: Kīlauea, Mauna Kea, Mauna Loa and Hualālai. Notably, Kīlauea has been erupting for the past 25 years. The young Hawaiian volcanoes, such as Mauna Loa, are considered shield volcanoes, which are formed from fluid theoleiitic basalt lava that develops gentle shield-like slopes. As the hot-spot moves past the main vent, the magma on the surface crystallizes and fractionates, producing alkalic material

(Wright and Helz, 1987). Sporadic eruptions alter the smooth topography and disperse ash and other volcanic matter around the Island. These events shape the unique topographic features of the Hawaiian Islands (Figure 2-2). Although infrequent, the rejuvenation-stage eruptions produce higher levels of alkaline material, which further develop soil resources on the Islands (Vitousek, 2004). It is with these phenomena do Hawai'i see such high soil diversity.

The coupling of Hawai'i Island's various mountain ranges with vast pastureland and flatlands deflect wind systems, creating its many micro-climates. An example is the climate of Kona and Leeward Hawai'i Island. Although Kona and Western Hawai'i Island are relatively dry compared to Hilo and Eastern Hawai'i Island, the topological features of Hualālai and Mauna Loa force incoming northeasterly tradewinds to circulate and rise along the Leeward slopes (Giambelluca et al., 2013). This uplift creates the perfect climate for Kona coffee.

Hawai'i Island is the only Hawaiian island that exhibits all 10 of the 14 Köppen Climate Classifications and displays 11 of the 13 known terrestrial ecosystems on earth (HCDV, 2010). The localized climates and relatively large elevation variability produce rainfall in the range of 200mm/yr (8in/yr) to over 7500mm/yr (300in/yr) above the trade wind inversion (2000m) and windward mid-elevation slopes near Hilo, respectively. Annual temperature averages from 3°C (37°F) on mountain tops to 34°C (94°F) near shores. The physical and climatic diversity of Hawai'i Island create an agriculturally supportive landscape, which must be evaluated for potential increase in agricultural efficiency.

2.3 Fresh Water on the Hawaiian Islands

Although groundwater is not discussed thoroughly in this thesis, it should be noted that the hydrogeology of the Islands is especially hard to map due to the different types of volcanic rocks (lava, intrusive dikes and pyroclastic deposits) as well as flows (a'a and pāhoehoe) that form the Islands. The sequences of flows produce uncorrelated and discontinuous systems of freshwater lenses, dike-impounded zones and perched aquifers. Because of these phenomena, it is hard to determine groundwater flow and discrete aquifer boundaries with conventional modeling. However, due to the fact that Hawai'i is an island and there is limited irrigation compared to precipitation, it can be assumed that most groundwater and surface water empties into the ocean. This is an important assumption when estimating crop water requirements (Chapter 4). The island-scale hydrologic analysis adopted here is different from others, including those of Smith (2011) and Figueroa (2012), in which political and aquifer boundaries were assumed to be aligned.

2.3.1 Focus on Hawai'i Island

On an island-wide scale, there is significantly higher recharge than withdrawal from groundwater. This is largely due to the permeable lava rock, through which precipitation readily percolates into freshwater lens and other aquifer systems. A Hawai'i Island water-budget model by Engott (2011) estimated an annual recharge of 6594 MGD. In 2005, 2014 and 2015, The County of Hawai'i and The Commission on Water Resource Management (CWRM) reported groundwater withdrawals of 96, 101 and 99 MGD, respectively. Even considering a high margin of error for pump reporting, groundwater storage is rarely exhausted on an island-scale. There are local overrides from smaller aquifer systems such as those of Waimea and Kohala, where intensive agriculture and high withdrawals occur. There are also challenges with surface water diversions either from lack of sources or infrastructure. These problems are, however, generally manageable with sufficient investment.

The allocation model in this thesis assumes that all crops are rainfed, which is a reasonable assumption given that approximately only 10% of all cropland on Hawai'i Island is irrigated (USDA NASS, 2012).

2.4 Soil Properties of the Hawaiian Islands

Kaua'i is the oldest main Hawaiian Island and is therefore the most eroded, as evident by Waimea Canyon. Hawai'i Island is the youngest of the Islands and is home to the younger Mauna Kea and Mauna Loa volcanoes. Between these Hawaiian Islands are 10 out of 12 known soil orders with Kaua'i having all 10, and Hawai'i Island having 6 (Figure 2-3). The 2 absent soil orders are gelisols and alfisols. Gelisols are only present in extremely high elevations, the Arctic and Antarctica. Alfisols are similar to ultisols, which are widely present on Kaua'i and O'ahu.

UH–CTAHR Soils of Hawai'i SCM-20 — Sept. 2007

Table 1. The areas (in acres) of soil orders on the six main Hawaiian Islands.

Soil order	*Kaua'i*	*O'ahu*	*Moloka'i*	*Lāna'i*	*Maui*	*Hawai'i*	*Total*
Andisol	14,499	3794	5555	0	99,245 [a]	695,381	818,474
Aridisol	4,616	7431	1588	0	14,204	41,126	68,965
Entisol	4,093	5438	4545	1247	8352	14,998	38,673
Histosol	6095	172	0	0	5762	527,890	539,919
Inceptisol	21,307	16,791	12,227	53	21,805	51,046	122,513
Mollisol	24,867	38,466	8794	11,791	66,917	13,018	163,853
Oxisol	76,638	83,079	27,941	16,703	12,156	0	216,517
Spodosol	4105	0	1892	0	0	0	5997
Ultisol	14,381	45,861 [b]	6387	1129	21,854	0	89,612
Vertisol	3,069	25,096	2283	3650	0	0	34,098

[a] This acreage of Andisols on Maui includes 45,836 acres mapped to a mixture of Andisols and Histosols and 12,351 acres mapped to a mixture of Andisols and Spodosols.
[b] This acreage of Ultisols on O'ahu includes 13,442 acres mapped to a mixture of Ultisols and Inceptisols.

Figure 2-3: Soil Orders in Hawaiian Islands by Area. Source: Deenik et al., 2007

The immense array of soil orders present on the Hawaiian Islands is evident because of the intense variability in climate, age, parent material and topography. With Kaua'i and O'ahu being the oldest of the Islands, there is more erosion, weathering, translocation, transformations and other large-scale biogeochemical processes happening. This is apparent from the prevailing areas of oxisols, ultisols and spodosols, all soil orders with high-weathering properties (Figure 2-4). Contrasting are the abundant areas of entisols, inceptisols and lava fields on the younger islands of Hawai'i Island and Maui (Figure 2-5). Entisols and inceptisols are weakly developed with little to no transformations within the soil. With the coupling of low seasonal climatic variability and a broad soil canvas, the Hawaiian Islands have become a thriving agricultural zone with high crop yielding potential.

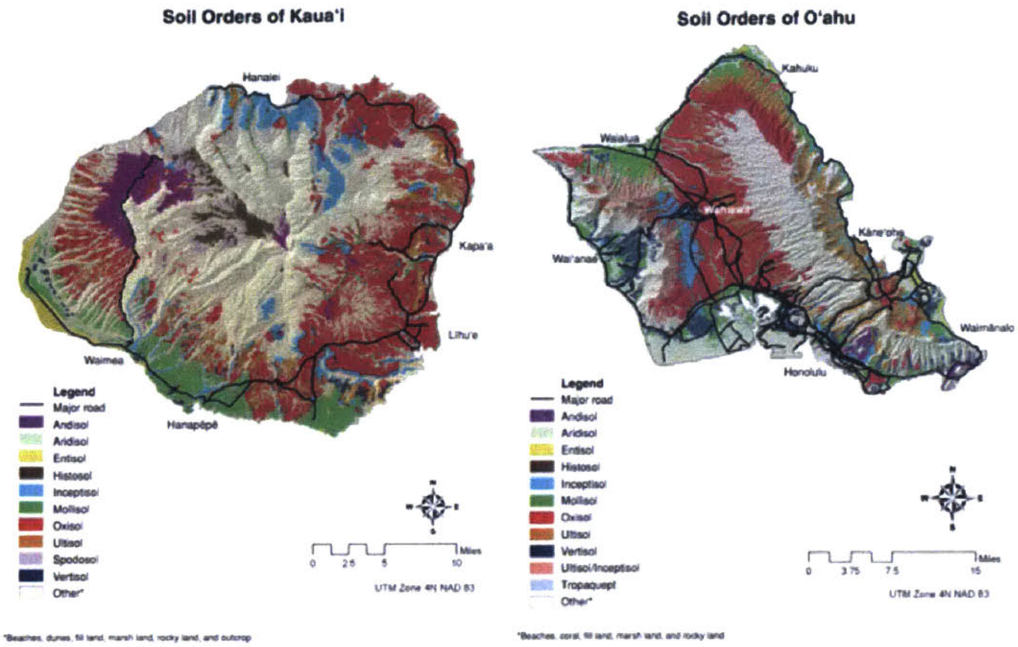

Figure 2-4: Kaua'i and O'ahu Soils. Source: Deenik et al., 2007

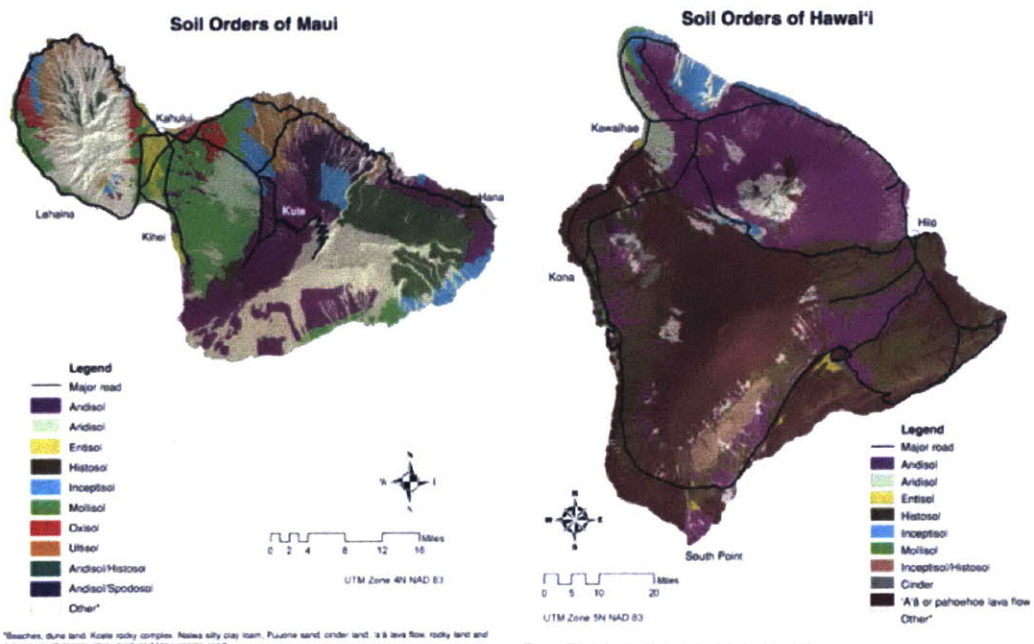

Figure 2-5: Mau'i and Hawai'i Island Soils. Source: Deenik et al., 2007

2.4.1 Focus on Hawai'i Island

As seen in Figure 2-6, Hawai'i Island consists largely of andisols, aridisols, histosols and inceptisols. North Hawai'i Island and Ka'ū andisols support vast pastureland, forests, macadamia, coffee, wild vegetation and small, diversified farms of various crops including corn and sweet potato. The andisol soils form from volcanic ejecta, ash, pumice, cinder and lava. The material is further weathered and transformed into alumino-silicate and amorphorous poorly crystalline minerals such as allophane (Al_2O), imogolite ($Al_2SiO_3(OH)_4$) and ferrihydrite (Fe_2O_3-$0.5(H_2O)$) (USDA, 2013). The structure of these minerals and clays are such that they produce fertile and productive soils with extremely high water holding capacity, stable aggregation and low bulk density in addition to naturally high organic matter content in the surface layers (Dennik et al. 2007). However, due to andisol's large populace of aluminum and iron clays, exposed hydroxylated surfaces and protonated hydroxyl groups, the macronutrient phosphorus is readily sorbed, often through inner-sphere complexation. In some cases, this sorption is irreversible, as found by Wada (1985) and McBridge (1994). Consequently, a large effort by Hue, Ikawa and Huang (1997) and other scientists has been put into quantifying phosphorus fertilizer usage on Hawaiian soils, as it is one of the most limiting nutrients on the Islands.

West Hawai'i Island and Hilo areas have large extents of histosols, the next predominate soil order on Hawai'i Island. Histosols are defined by their thick (at least 40mm) organic matter surface layer, which often has greater than 12-18% organic carbon. Like andisols, histosols have low bulk densities as well as high water and nutrient holding capacities (USDA, 2013). In these soils, organic matter sources are larger than sinks so histosols are typically found in low lying areas with wet anaerobic conditions and slow microbial decomposition rates. Depending on the climate, these soils range from slightly to very acidic and may contain high levels of soluble toxic aluminum ions. Histosols are favorable to 'ōhi'a trees that have been cleared for macadamia, papaya and coffee (Deenik et al. 2007). The grayed areas atop Mauna Kea and Mauna Loa, as well as the patches around South and East Hawai'i Island

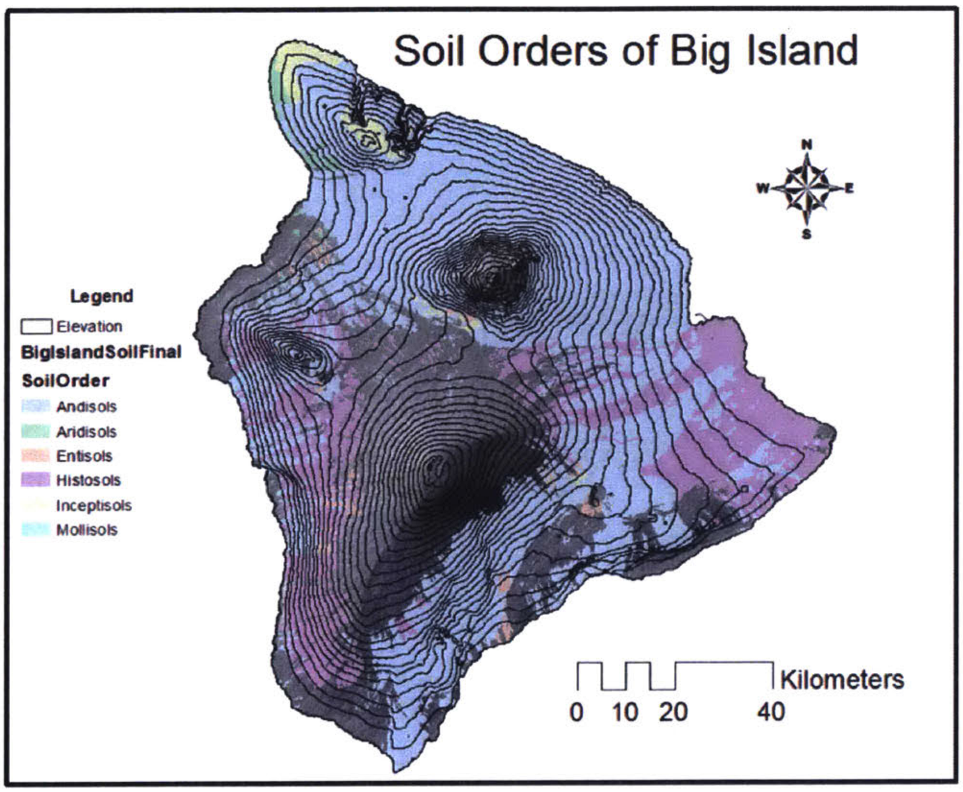

Figure 2-6: Focused Soil Map of Hawai'i Island. Data Source: USDA NRCS

are classified as a'a or pāhoehoe lava fields, which have no soil development and are unable to support crops.

The diversity in soil types in addition to their physical and chemical properties such as depth, cation exchange capacity and pH affect the suitability of crops, making the soil setting of Hawai'i Island a crucial factor in determining potential agricultural land. The next chapter connects Hawai'i Island's diverse climates and soils to its agricultural history and discusses Hawaiian agriculture in chronological order from pre-contact to today.

Chapter 3

A Brief History of Hawaiian Agriculture

3.1 Ancient Hawaiian Agriculture

It is believed the Ancient Polynesians voyaged to the Hawaiian Islands one to two millennia ago, bringing with them their most valued foods, tools and medicines. Among others, kalo (taro), 'uala (sweet potato), ko (sugarcane) and mai'a (banana) were the bulk of foodstuffs. In addition, 'awapuhi (wild ginger), 'ōlena (tumeric), 'awa (kava), gourds and fibers were brought for medicines, tools and instruments (Kapua and Mower, 1980). At least 32 different species of plants in addition to dogs, pigs, chickens and rats were introduced by the Ancient Polynesians to the Hawaiian Islands (HCDP, 2010; Lee and Bittenbender, 2008).

Under the rule of the King, the land, or 'āina was divided into subdivisions from the larger districts of the moku'āina to the smaller subdivisions of the kalana, okana and ahupua'a (Kamakau et al., 1964). Each ahupua'a, analogous to a watershed or catchment, spanned mauka to makai, or mountain to ocean, and included fisheries, beaches, cultivable lands and forests. This allowed the inhabitants to access a complete spectrum of reserves.

Each subdivision was held accountable for producing foods and other commodities for both cultural and subsistence purposes, epitomizing natural resource management and community responsibility (McGregor, 2008). This system promoted the brilliant and sustainable engineering of the Native Hawaiians, as they learned how biophysical resources moved from the mountain top to the ocean floor.

The Ancient Polynesians carefully cultivated on rain-fed drylands, irrigated wetlands and colluvial slopes and, at that time, produced some of the largest farms in Polynesia (Ladefoed et al., 2009). The rain-fed drylands were primarily used for sweet potato, yams, dryland taro and sugarcane. This type of cultivation occurred in the younger islands of Hawai'i Island and Maui. Irrigated wetlands sustained large lo'i, or pond field terraces of taro and were the most intensive type of farming on the Hawaiian Islands. The nutrient-rich colluvial slopes offered fertile land for root, tuber, tree crops, bananas, sweet potato, yams, breadfruit, ti and more. Although the colluvial slopes were not as intensely cultivated as the drylands and wetlands, they offered the largest range of crops. Kurashima et al. (2011) confirmed this for the island of Moloka'i. Finally, sustainable aquaculture expansions via stonewalled fishponds enclosed up to 200ha (500 acres) of ocean and produced 67kg/ha (60lbs/acre) of fish (Kurashima et al., 2011). In other cases, there were also freshwater and brackish fishponds as well as mariculture networks (Evensen and Chaston, 2008). It was from these agricultural practices that the pre-contact Hawaiians thrived and sustained themselves.

Practices such as seasonal rotations and strict kapu (prohibitions and regulations) in addition to sustainably engineered systems and other management techniques enabled the Native Hawaiians to hunt, gather, fish and farm in harmony with the natural resources of the land and ocean (Smith and Pai, 1992). With no foreign communication or aid, the pre-contact Hawaiians soundly managed their ecosystem and sustained up to an estimated one million people (approximately 0.2M to 1M people), a true testament to the current issue of food self-sufficiency (Schmitt, 1968; Stannard; 1989; Dye, 1994).

3.2 Emergence of Industrialized Farming

Captain Cook's arrival in 1778 to the Hawaiian archipelago began a new type of political regime that was economically-driven, which vastly altered the existing agricultural system in place for hundreds of years prior. With the onset of ships and other means of communication with the outside world, the Hawaiian Islands transformed into a trading and resting zone for whaling barges and passing merchants. During this time, Hawai'i began to export one of its first commodities to China: sandalwood (Page, 2007). This new engagement disturbed the ahupua'a management system and perturbed the Hawaiian ecological equilibrium.

The sandalwood trade connected Hawai'i with the global market, which led to a cash-motivated agricultural system. Eventually, the sandalwood trade declined due to resource exhaustion, but the pressure to produce export commodities sustained, causing a shift from the Ancient Hawaiian ahupua'a structure to a mono- and cash-crop system. The rise and fall of these crops, mainly wheat, sugar, pineapple, and papaya, display the transition from Hawai'i's once 100% independent agricultural system to its highly dependent and non-self-sufficient state today.

As trade increased, American, Chinese, Japanese, Filipino and other foreign workers began to immigrate, introducing new technologies and foods like rice, wheat, onion, cabbage, and cows as well as canned, dried and salted goods (Lee and Bittenbender, 2008). The gradual change in palette and diet made flour a desirable ingredient in cooking, but was also largely unavailable, if not rotten and inedible. In the mid 19^{th} century, Maui and O'ahu began to grow 0.6-5.9km^2 (140-1200 acres) of golden wheat, respectively, with sufficient infrastructure for processing. The production was enough to be 100% self-sufficient and more, but was quickly suppressed by the Gold Rush in California and the rising economic opportunity of sugar (Lee and Bittenbender, 2008). The short-lived wheat industry opened new markets for cash crop export, including sweet potato for Gold Rush workers and sugarcane (Melrose and Delparte, 2012). This was the beginning of the Plantation Era.

3.3 The Plantation Influence

The phrase "Hawaiian agriculture" is incomplete without sugar and pineapple plantations. The plantations significantly influenced the Hawaiian culture, economy, land and water resources, and is currently impacting the agricultural self-sufficiency trends today. Under the sugar industry, the landscapes of the Islands were reformed (Figure 3-1). About 96% of the entire sugar industry was owned by five major companies that provided housing, schools and stores for the plantation workers (Page, 2007). This new type of lifestyle motivated thousands of Asians and Europeans to immigrate, which was the beginning of significant changes to Hawai'i.

The rise of the sugar and pineapple industry in Hawai'i from 1883 not only influenced and shaped island culture today, but also heavily altered the soils and land resources. In 1994, 87% of all agricultural land was devoted to sugar, pineapple or macadamia farms (Lee and Bittenbender, 2008). These massive plots of converted lands were sprayed with enormous quantities of fertilizer, pesticides and herbicides with little to no regard for future environmental quality (Cutler et al., 2016). Most of these lands were left eroded, nutrient-depleted and weed-filled.

Plantations impacted water resources by diverting and pumping large quantities of water in response to the increasing market demand for sugar. In 1988, The County of Hawai'i estimated 73MGD of water was pumped without sugar and 104MGD with sugar, meaning sugar plantations accounted for 30% of groundwater withdrawal. From this heavy pressure, sugar plantations essentially changed the hydrology of the Island by artificially increasing recharge by 25% over natural conditions in some area from uses of ditches and tunnels (Izuka et al., 2005).

Through the early 19^{th} century, the sugar and pineapple industries flourished economically as technology like the refrigerated container became available. The Hawaiian economy grew, bringing in more types of imported foods at lower prices (Melrose, 2012). This began to change the mindset of local people, who started to depend on grocery stores instead of their backyard.

During World War II, 30% of workers left for the military (Auchter, 1951) and

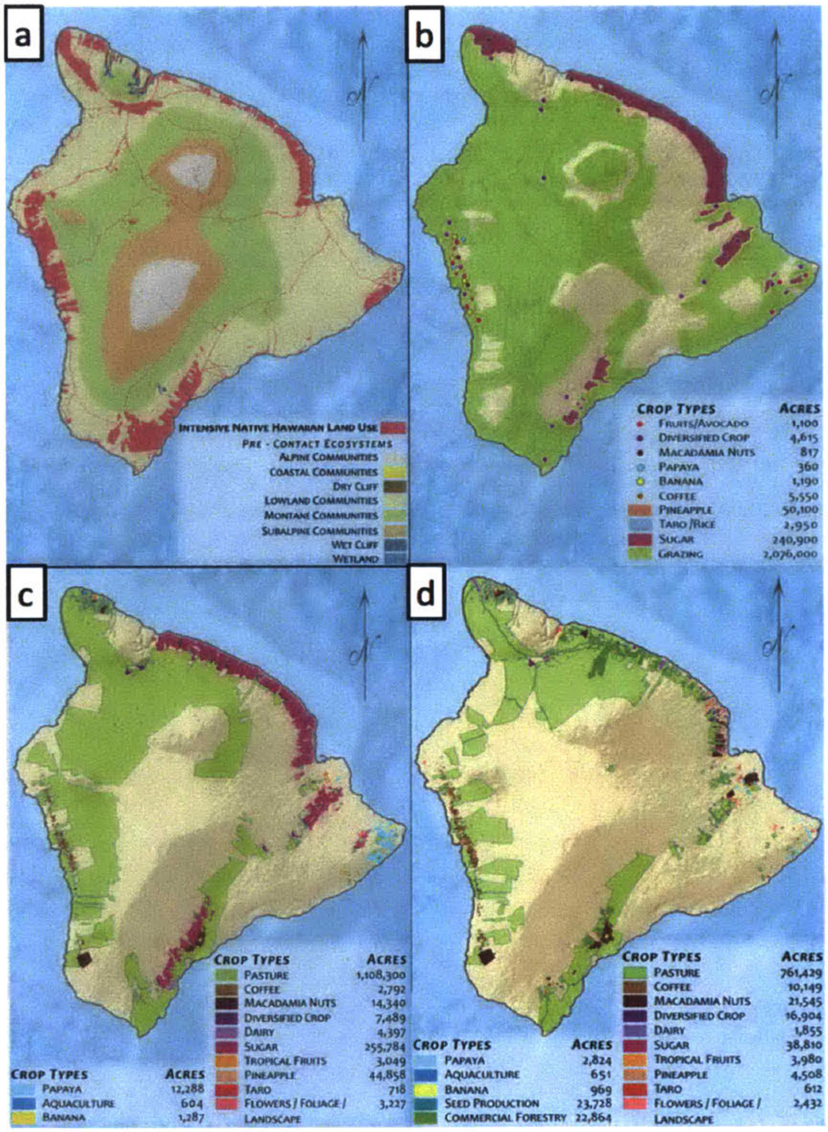

Figure 3-1: Evolution of Land-use Change in Hawaii. (a) Estimated pre-contact native hawaiian land utilization - source: Ladefoged et al., (2011) (b) Hawai'i Island 1937 - source: Territorial Planning Board Land Utilization Study (c) Hawai'i Island 1980 - source: Hawai'i Department of Agriculture (d) Hawai'i Island 2015 - source: Hawai'i Department of Agriculture. Figures by Melrose et al., 2016

plantation workers unionized, leading to a large strike in 1946. As a result, the prosperous pineapple plantations started to decline as companies looked to the Philippines, Thailand and Taiwan for cheaper labor and larger areas (Bartholomew et al., 2012). This, in addition to competition from South America and the Caribbean as well as the successful synthesis of high-fructose corn syrup challenged the economic feasibility of sugar plantations in Hawai'i. From the 1960s through the 1980s, the pineapple and sugar plantations began to close, leaving many workers displaced and unemployed (Page, 2007).

During the fall of the Plantation Era from 1980 to 2000, state-wide water consumption decreased by 52% from approximately 1400 MGD to 730 MGD (Ferguson and Moravcik, 2008). This freed up water for more diversified agriculture. The sequencing of Hawaiian agriculture from the ahupua'a to sandalwood to wheat, sugar and pineapple had a dominant influence over the biophysical landscape. Because of this, it is essential in having a thorough understanding of the history to comprehend the current status of the land-use and agriculture today.

3.4 Hawaiian Agriculture Today as Defined by Yesterday

As described in Section 3.2, the plantation mono-culture systems of sugarcane, pineapple and other cash crops greatly transformed the biophysical landscape and economic conditions of Hawai'i. These relatively recent shifts coupled with the growing issue of food self-sufficiency make it necessary to assess current environmental resources for potential expansion and allocation. First, it is necessary to gain an insight on current agriculture and shipment trends to understand exactly where Hawai'i stands today.

3.4.1 Present Food Self-Sufficiency

Sugar, pineapple and macadamia farms maintained 87% of Hawaiian agricultural lands in 1994. Ten years later, sugar plantation acreage fell from approximately

490km^2 to 175km^2 (121,000 to 43,000 acres) and revenue dropped 60% (Lee and Bittenbender, 2008). The closure of large stakeholder plantations unlocked smaller parcels of land for people to farm diversified agriculture. As a result, Hawai'i truck and exotic crops including nursery flowers, seeds and avocado saw impressive growth in market share despite an economic downturn in the 1990s (Lee and Bittenbender, 2008). In 2016 the last sugar plantation was converted to diversified agriculture in Pu'unene, Maui (Wang, 2016).

Farmland area over The State of Hawai'i was compiled from the earliest recorded (1940) annual agricultural statistics book published by the USDA NASS to the most recent bulletin posted in 2011 (Figure 3-2). The results illustrate the immense area occupied by the sugar and pineapple plantations (expressed in thousands of acres) from the early 1940s through the 1980s. As plantations closed, other cash crops like macadamia and coffee gained attention, surpassing sugar area around 1985 and 1995, respectively.

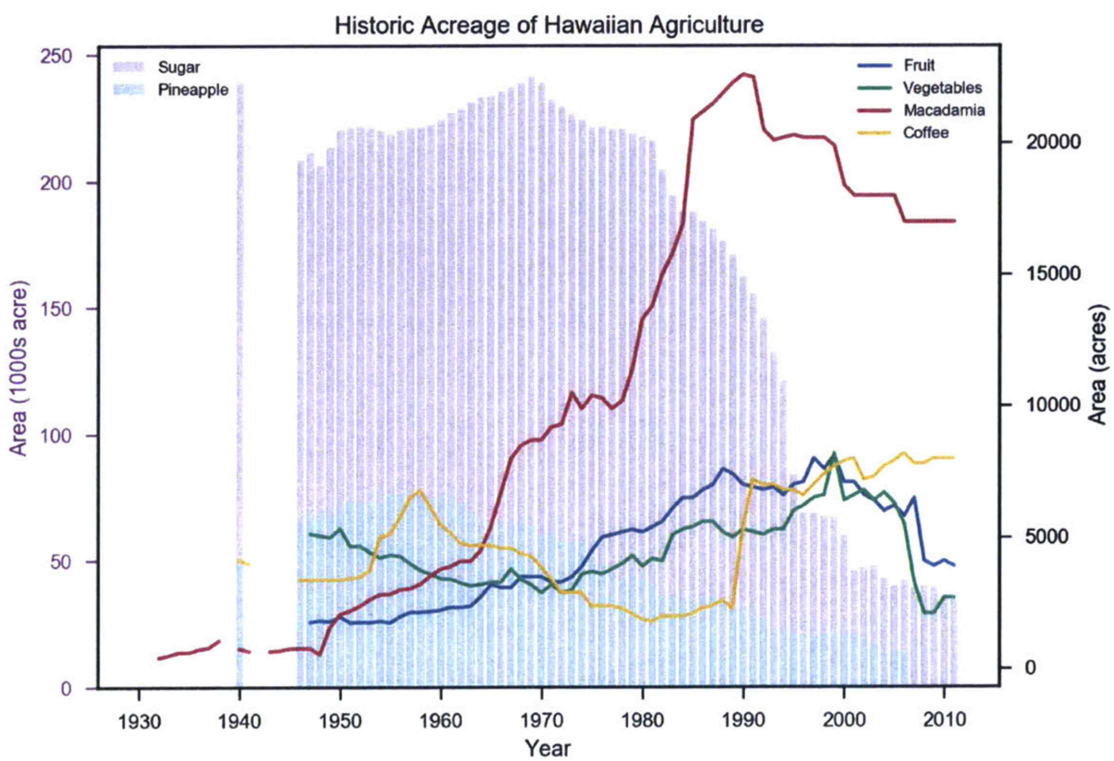

Figure 3-2: Historic Acreage of Hawaiian Agriculture - Data Source: USDA, NASS

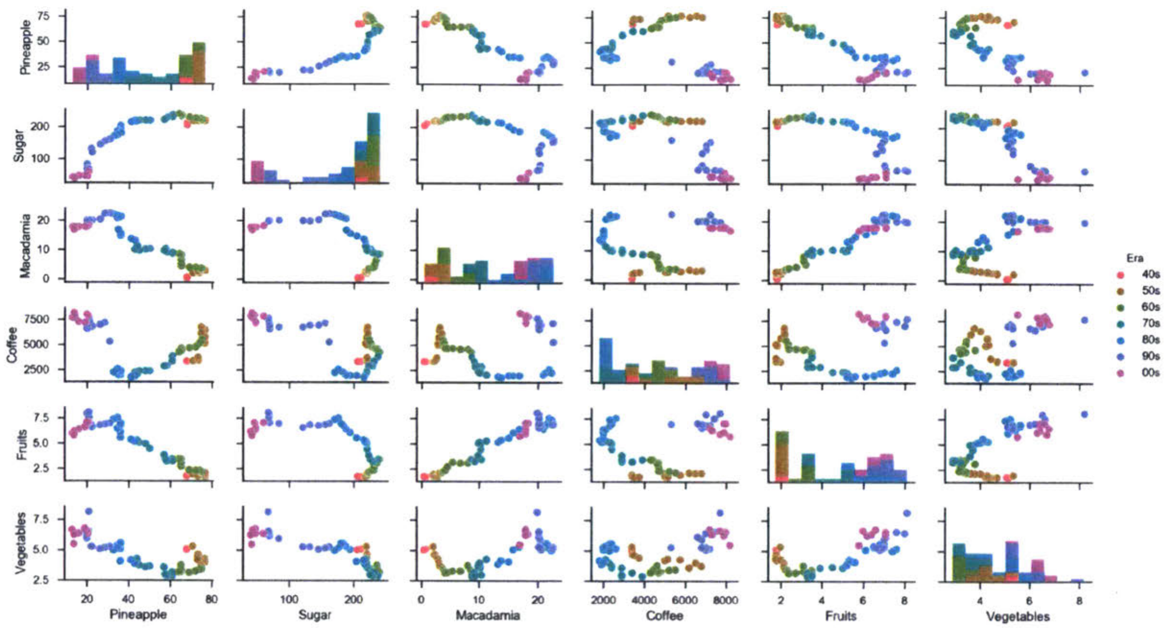

Figure 3-3: Historic Correlations Between Plantation Crops and Diversified Agriculture. Data Source: USDA NASS 1940-2011 Annual Statistics Bulletin

The trends also reveal the increase in diversified fruits and vegetables, which imply the transition from large stakeholder plantations to smaller farms. Figure 3-3 displays the correlations between pineapple, sugar, macadamia, coffee, diversified fruit and vegetable crop areas over the course of 70 years (1940s-2011). It is apparent that fruits, vegetables and macadamia were negatively correlated with the pineapple and sugar crops, while relatively positively correlated with each other. In addition, pineapple and sugar were positively correlated, describing the rise and fall of both plantations in the same relative time span.

Despite the recent variability in acreage due to climatic or economic conditions, diversified crops are certainly gaining traction, further motivating the need to quantitatively analyze food self-sufficiency and natural resources.

Calculating Past and Present Food Self-Sufficiency

The USDA NASS maintained approximately 70 years of market supply data from the 1940s to 2011. This data provides the only insight on the status of food self-sufficiency in terms of particular vegetables, fruits and livestock. From these statistics, a "percentage of self-sufficiency" POS for The State of Hawai'i can be calculated to analyze general self-sufficiency trends:

$$POS_y = \frac{\sum_{c,y} LP_y^{(c)}}{\sum_{c,y} FI_y^{(c)} + LP_y^{(c)}} 100\% \tag{3.1}$$

Where, POS_y is the percentage of self-sufficiency in year y,
$LP_y^{(c)}$ is the amount of locally produced food (000s lbs) for crop c in year y and
$FI_y^{(c)}$ is the amount of food imported (000s lbs) for crop c in year y.

POS data was compiled from 1947 to 2008. Although POS patterns fluctuated (Figure 3-4), there was a relatively decreasing trend as Hawai'i became more dependent on outside sources for fresh fruits and vegetables.

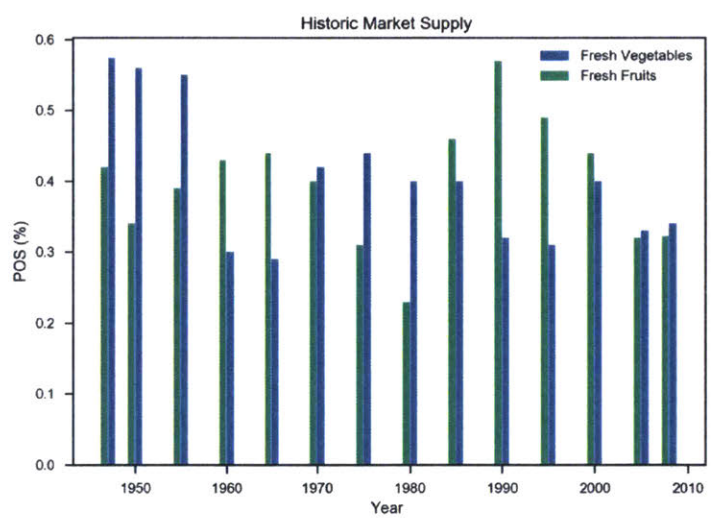

Figure 3-4: Percent of Self-Sufficiency for the State of Hawai'i. Data Source: USDA NASS 1940-2011 Annual Statistics Bulletin

The latest 2008 POS is the most current statistic to evaluate self-sufficiency due to a termination of bookkeeping. In 2008, Hawai'i stood at 32% and 34% POS for fresh fruits and vegetables, respectively. These values approximate the current overall status of crop dependence and correspond appropriately with the estimated 85% food dependence.

Note that the earliest USDA NASS records in the 1940s show an estimated market supply for fresh fruits and vegetables to be in the range of 58% to 47%, a much higher

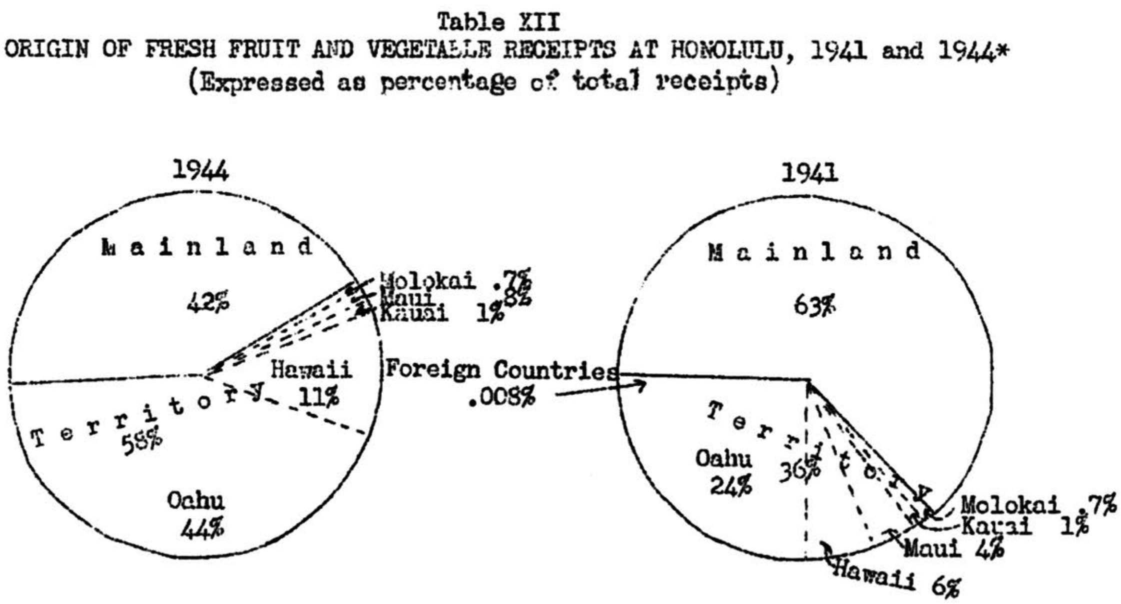

Figure 3-5: Origin of Fresh Fruits and Vegetables for 1941 and 1944. Source: USDA NASS Annual Statistics Bulletin (1945)

food independence compared to today (Figure 3-5).

Vegetables

As stated in Subsection 3.4.1, the most recent agricultural bulletin places Hawai'i at approximately 34% self-sufficient overall for vegetables. From Figure 3-4, the 2008 vegetable POS for Hawai'i has remained relatively stable for the past 70 years, but was much higher pre-1950s. Looking at particular vegetable POS values in Table 3.1, it is apparent that specific vegetables are close to being 100% self-sufficient. However, others such as broccoli, lettuce, celery and dry onion are not as high. In this study, tomato, broccoli, celery, cucumber, eggplant, lettuce, dry onion and sweet potato are considered. The reasons for this choice is primarily due to the availability of suitability and yield data in addition to the baseline data accessible to evaluate these specific crops and their demand in Hawai'i based on inshipment trends.

Furthermore, Hawai'i Island is of particular interest because of its potential for agricultural intensification and expansion. Given Hawai'i Island contributes to only 19% of diversified crop (Melrose et al., 2016) acreage while O'ahu alone contributes

58%, it is a pressing question to see the potential of Hawai'i Island. Certainly, more vegetables can be included into our analysis for a more in-depth evaluation.

Figure 3-6 highlights the area and production of diversified fruits[1] and vegetables[2] in addition to the specific crops of banana, papaya and sweet potato for The State of Hawai'i. It is important to note the variability in vegetable acreage and its decline from the early 2000s to today.

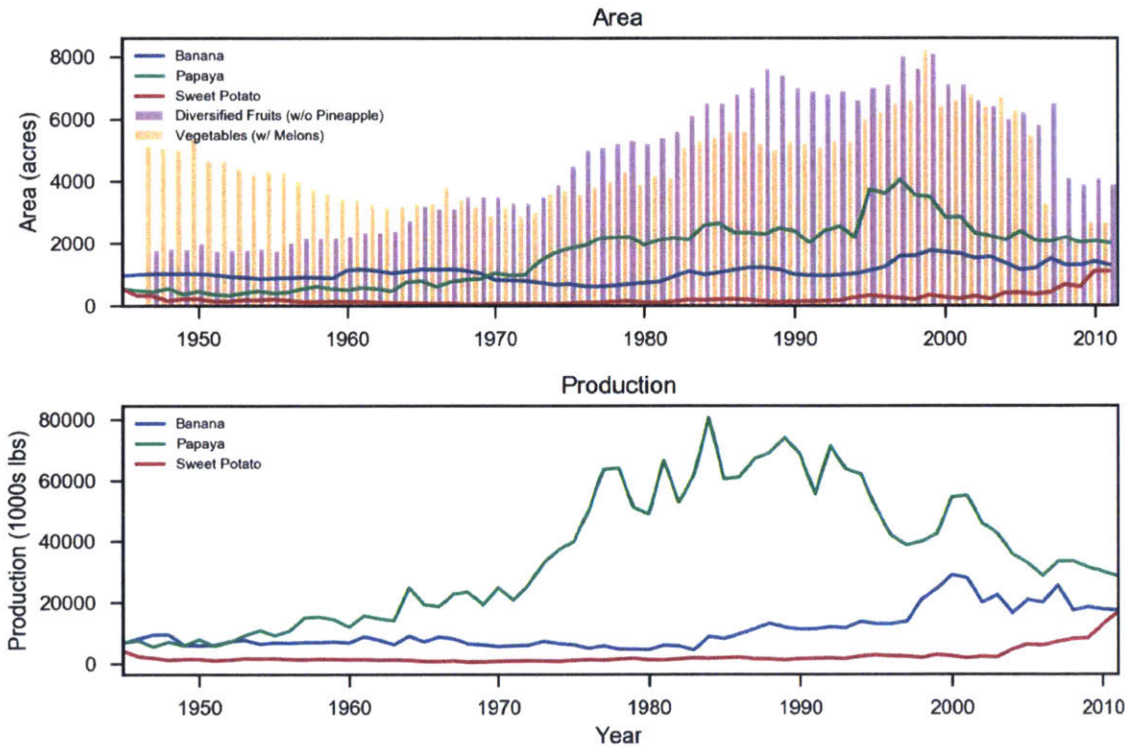

Figure 3-6: Historic Fruit and Vegetable Area and Production with Banana, Papaya and Sweet Potato for The State of Hawai'i

Fruits

In 2008, The State of Hawai'i had a fruit POS of 32.2%, slightly lower than that of vegetables. From Figure 3-4, it is apparent that fresh fruit POS were very variable

[1]The USDA NASS "diversified fruits" include avocado, banana, guava, papaya and passion fruit - Note: some fruits are added or removed in the period of market supply record.

[2]The USDA NASS "vegetables" include snap beans, cabbage, celery, sweet corn, cucumbers, daikon, eggplant, lettuce, green/dry onion, green peppers, romaine, italian squash, sweet potato, taro, tomato, watercress, watermelon and other - Note: some vegetable crops are added or removed in the period of market supply record.

Table 3.1: 2008 Vegetable Self-Sufficiency

Selected Crops	2008 POS (%)
Snap Beans	56.5
Bittermelon	65.4
Broccoli	6.5
Chinese Cabbage	87.3
Head Cabbage	80.1
Mustard Cabbage	82.2
Celery	6.6
Sweet Corn	78.3
Cucumber	77.6
Eggplant	55.1
Lettuce	11.0
Dry Onion	7.0
Sweet Potato	83.4
Romaine	9.7
Taro	30.1
Watercress	99.5

from the 1940s to present, reaching to more than 50% self-sufficient in the 1990s. The decreasing trend of self-sufficiency for Hawaiian fruits is concerning and should not be ignored.

Hawai'i Island accounts for an estimated 78% of the approximate 16km^2 (4000 acres) of Hawaiian land devoted to tropical fruits. It is important to note that Hawai'i Island produces 55% and 88% of bananas and papayas (in terms of crop area) for The State of Hawai'i, respectively. These agricultural statistics show how dominant Hawai'i Island is with tropical fruits, bananas and papayas compared to the vegetable category.

In Figure 3-6, a similar trend with tropical fruit persists today, with a decline in papaya production possibly due to the increasing awareness and concerns about genetically modified (GM) varieties. The variability in fruit acerage also presses the issue of declining POS for The State of Hawai'i.

Less crop POS data are available[3] for fresh fruit (Table 3.2). From the data, it is apparent that no fruit is at least 50% self-sufficient, with the citrus varieties less

[3]Only selected fruits with sufficient data were included.

Table 3.2: 2008 Fruit Self-Sufficiency

Selected Crops	2008 POS (%)
Avocado	33.7
Banana	47.1
Grapefruit	3.4
Lemon	1.5
Lime	3.7
Tangerine	4.7

than 5%. Although this can be attributed to the climate and growing suitability of crops, it is essential to add known productive fruits in the optimization model. In this study, avocado and banana are evaluated. These crops are selected primarily due to the availability of suitability and yield data and to their inherent capability to expand on the Island. Like vegetables, more fruits can be added to the model with appropriate information.

Chapter 4

Estimation of Crop and Non-Crop Water Requirements

4.1 Overview

The thesis optimization model in Chapter 5 imposes physical water balance constraints when allocating land resources. Therefore, accessing specific crop and non-crop water requirements are necessary to quantify the outward fluxes of water.

Crop and non-crop water requirements are usually measured as evapotranspiration (ET) and are obtained from modeled data. Often, these datasets are unbalanced when considering independent precipitation (R) and lateral flow information and must be corrected via estimation to obtain a more dependable quantification that is physically bounded. Due to the readily available geophysical, meteorological and topographical data at high spatial resolution, we are able to implement a more focused and representative study that estimates crop and non-crop water requirements specific to Hawai'i Island.

The estimation of crop and non-crop water requirements are achieved through a least-squares data fitting formulation, which minimizes the misfit between modeled ET and approximated ET under physical water balance constraints (Refer to Section 4.2). The main outputs are crop and non-crop water requirements via ET estimates approximated with FAO Kc coefficients. The estimated Kc factors for the specific crops and non-crop are then assigned to crops considered in the allocation model in Chapter 5. The relationships between Kc coefficients and ET are documented extensively (Allen et al., 1998) and are defined as:

$$ET_p^{(c)} = Kc_z^{(c)} RET_p^{(c)}; \quad p \in \Omega_{grid},\ z \in \Omega_{zone},\ c \in \Omega_{ALU} \tag{4.1}$$

$$ET_p^{(nc)} = Kc_z^{(nc)} RET_p^{(nc)}; \quad p \in \Omega_{grid},\ z \in \Omega_{zone} \tag{4.2}$$

Where, $ET_p^{(c)}$ is the estimated ET for crop c in pixel p,
$ET_p^{(nc)}$ is the estimated ET for non-crop in pixel p,
$Kc_z^{(c)}$ is the FAO coefficient for crop c in zone z,
$Kc_z^{(nc)}$ is the FAO coefficient for non-crop in zone z,
$RET_p^{(c)}$ is the reference ET for crop c in pixel p and
$RET_p^{(nc)}$ is the reference ET for non-crop in pixel p.
Ω_{grid} is the set of all pixels in the computational grid,
Ω_{zone} is the set of Kc coefficient zones and
Ω_{ALU} is the set of crop categories defined in the ALU.

From 1990, the FAO standardized RET to be computed via the Penman-Monteith method (Equation 4.3). Penman-Monteith is widely accepted because it includes radiation, air temperature, humidity and wind speed. Using a Penman-Monteith-derived RET is appropriate since it captures the local climate effects. Formally, RET is defined as the reference ET of a well-watered grass with uniform height of 0.12m, actively growing and shading the ground. Additionally, surface resistance is set to 70sm^{-1} and albedo 0.23.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{4.3}$$

Where, R_n is net radiation,
G is soil heat flux,
$(e_s - e_a)$ is vapor pressure deficit of the air,
r_a is mean air density at constant pressure,
c_p is the specific heat of air,

D is slope of saturation vapor pressure temperature relationship,

g is the psychrometric constant,

r_s is the bulk surface resistance and

r_a is the aerodynamic resistance (Allen et al., 1998).

The Kc coefficients are the ratio of ET to reference grass ET or RET. Kc coefficients adjust the RET to account for four primary factors: vegetation height, albedo reflectance, canopy resistance and soil evaporation. Any changes to Kc are highly vegetation-specific and are costly to measure over large areas. Therefore, estimation is useful to back out Kc values from approximated ET products.

Figure 4-1 displays the sequence of converting RET values to the adjusted $ET_p^{(c)}$ and $ET_p^{(nc)}$ values. Although Kc coefficients typically vary with time, in this study, the average Kc coefficient values over the year are approximated. Furthermore, Kc coefficients are assumed to include Ks, the crop stress coefficient, which accounts for any water or environmental stress experienced by the vegetation.

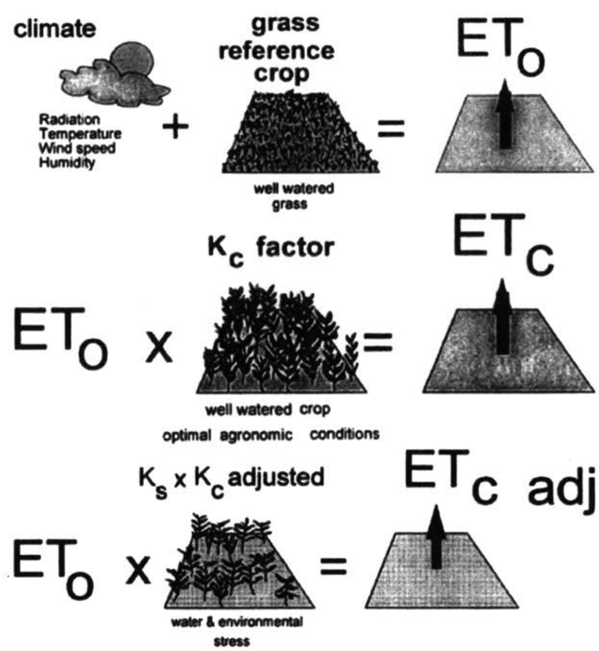

Figure 4-1: Reference ET (ET_o), Standard ET (ET_c or RET) and Non-Standard ET ($ET_{c\,adj}$). Source: Allen et al., 1998

4.2 Formulation

4.2.1 Objective Function

The objective function (Equation 4.5) is a constrained least-squares formulation that minimizes the error between AET and estimated ET for crop and non-crop at each pixel.

$$\hat{w} = \underset{\{w\}=\{ET_p^{(c)}, ET_p^{(nc)}, \bar{Q}_p\};\, c\in\Omega_{ALU}, p\in\Omega_{grid}}{\arg\min} J(w) \tag{4.4}$$

$$J(w) = \sum_{p\in\Omega_{grid}} \left(\sum_{c\in\Omega_{ALU}} \left(\frac{(AET_p^{(c)} - ET_p^{(c)})^2}{(AET_p^{(c)})^2} \right) + \frac{(AET_p^{(nc)} - ET_p^{(nc)})^2}{(AET_p^{(nc)})^2} \right) \tag{4.5}$$

$$ET_p^{(c)} = Kc_z^{(c)} RET_p^{(c)}; \quad ET_p^{(nc)} = Kc_z^{(nc)} RET_p^{(nc)}; \quad z \in \Omega_{zone},\ p \in \Omega_{grid},\ c \in \Omega_{ALU}$$

Where $J(w)$ is the objective function, which is minimized with vector $\hat{w}$ spanning $\mathbb{R}^{\Omega_{grid}(\Omega_K+2)}$,

$\bar{Q}_p$ is the estimated base and surface water flow for pixel p,

$AET_p^{(c)}$ is the measured actual ET for crop c in pixel p,

$AET_p^{(nc)}$ is the measured actual ET for non-crop in pixel p,

$ET_p^{(c)}$ is the estimated ET for crop c in pixel p,

$ET_p^{(nc)}$ is the estimated ET for non-crop in pixel p,

$Kc_z^{(c)}$ is the estimated FAO coefficient for crop c in zone z,

$Kc_z^{(nc)}$ is the estimated FAO coefficient for non-crop in zone z,

$RET_p^{(c)}$ is the reference ET for crop c in pixel p and

$RET_p^{(nc)}$ is the reference ET for non-crop in pixel p.

Ω_{grid} is the set of all pixels in the computational grid,

Ω_{zone} is the set of Kc coefficient zones and

Ω_{ALU} is the set of crop categories defined in the ALU.

4.2.2 Water Balance Constraints

The water balance constraints ensure a physically bounded solution. Equation 4.6 is a steady-state water balance that enforces net inflow to equal net outflow. Equation 4.7 ensures that the total input of water from R cannot be less than the total removal from ET. Equation 4.8 expresses that the estimated lateral fluxes at particular pixels must be greater than the average observed surface water flow recorded by USGS stream gauges at the respective pixels. This constraint is set because the least-squares optimization considers a control boundary inclusive of surface and groundwater flow.

$$\Delta t \sum_{n\in\Omega_{trib(p)}} \left(I_n - O_n\right) + \Delta t\left(R_p A_p^{(T)} - \left(\sum_{c\in\Omega_{ALU}} \left(ET_p^{(c)} A_p^{(c)}\right) + ET_p^{(nc)} A_p^{(nc)}\right)\right) - \Delta t \bar{Q}_p = 0; \tag{4.6}$$

$$p \in \Omega_{grid}$$

$$\Delta t I_p \geq \Delta t O_p; \quad p \in \Omega_{grid} \tag{4.7}$$

$$\bar{Q}_p \geq U_p; \quad p \in \Omega_{USGS} \tag{4.8}$$

Where, I_n is the inflow for pixel n,

O_n is the outflow for pixel n,

R_p is the rate of precipitation for pixel p,

$A_p^{(T)}$ is the total area in pixel p,

$A_p^{(c)}$ is the area of crop c in pixel p,

$A_p^{(nc)}$ is the area of non-crop in pixel p,

$ET_p^{(c)}$ is the estimated ET for crop c in pixel p,

$ET_p^{(nc)}$ is the estimated ET for non-crop in pixel p,

$\bar{Q}_p$ is the estimated base and surface water flow for pixel p and

U_p is the USGS historic surface water runoff at pixel p.

Δt is a scalar time-step set to 1 year.

Ω_{grid} is the set of all pixels in the computational grid,

$\Omega_{trib(p)}$ is the set of tributary pixels for pixel p,

Ω_{ALU} is the set of crop categories defined in the ALU and
Ω_{USGS} is the set of pixels where USGS gauges are located.

4.3 Preparation for Data Estimation

4.3.1 Data

The least-squares optimization model leverages high resolution data while keeping the processing and computation at a reasonable level. This is accomplished by feeding the model average ET and area values for each vegetation type within a larger general grid. Therefore, each pixel in the general grid has a unique ET and area for each ALU component and non-crop, resulting in highly precise measurements without having to evaluate at the data pixel size. This section begins with describing the various high resolution datasets that are used in the model then follows with the method of combining the datasets with the larger general grid.

Precipitation

The precipitation[1] (R) product (250m) is obtained from the Rainfall Atlas of Hawai'i, Geography Department at University of Hawai'i Manoa (Frazier et al., 2016; Giambelluca, et al., 2013) and is defined by the mean annual rainfall from 1978-2007 (30 year climatology). In the model, over 1000 stations throughout The State of Hawai'i were merged with PRISM rainfall analysis (Dayl et al., 2006), NEXRAD radar rainfall and other types of supplementary predictors to gain a consistent and continuous rainfall map. The stations consists of a compiled set of observations from the Plantation-era, USGS, HydroNet and other networks. Although there are few uncertainties in the rainfall measurements such as a consistent positive Pacific Decadal Oscillation phase over the 30 years as well as interpolation assumptions and imprecise station locations, we assume that the precipitation errors were minimized in the process and the resulting product is perfectly known.

[1]'Precipitation' and 'rainfall' are interchangeable in this study and includes rainfall and solid precipitation, but not fog drip.

Evapotranspiration

Reference Evapotranspiration (RET) and Actual Evapotranspiration (AET) (250m) are obtained from the Hawai'i Evapotranspiration Project, Geography Department at University of Hawai'i Manoa. The RET and AET are based on the Penman-Monteith formula (Equation 4.3). Giambelluca, et al. (2014) considered three separate models of wet-canopy, transpiration and soil evaporation to produce total ET. The model utilized satellite- and station-derived variables including vegetation density, plant stomatal control, soil moisture and humidity for ET calculations. The estimation assumes AET is measured imperfectly and is therefore subject to change in the least-squares optimization.

Agricultural Land-Use

The most recent 2015 agricultural land-use data (ALU) created by the Spatial Data Analysis and Visualization Lab (SDAV) at University of Hawaii Hilo is used in this study (Melrose et al., 2016). It consists of a categorical map with 15 different crop categories[2]: aquaculture, banana, coffee, commercial forestry, seed production, dairy, diversified crop, flowers/foliage/landscape, macadamia, papaya, pasture, pineapple, sugar, tropical fruits and taro. The study is based on 2011-2013 WorldView-2 satellite imagery and other geospatial datasets at high resolution. Only commercial agriculture with at least 3 acres of land were considered in the classification. The 2015 ALU dataset is used throughout this study as the baseline agricultural zoning for Hawai'i Island.

Runoff

Historic surface runoff (U) for major Hawai'i Island outlets are collected from the USGS National Water Information System (Table 4.1). The complex stream network and series of gulches on Northern Hawai'i Island make it infeasible to measure surface runoff at all outlets. Therefore, the four reported USGS surface runoff values are used

[2]All other lands not classified in the ALU are set as non-crop.

exclusively. We assume that the runoff measurements are perfectly known since the USGS gauges are accurate and their respective record lengths are sufficient.

Table 4.1: Historic USGS Surface Runoff Gauge Data

Stream Gauge	Name	LAT	LON	Avg. U (csf)	Record (yr)
USGS 16717000	Honoli'i	19.764	-155.152	122.1	48
USGS 16704000	Wailuku	19.712	-155.151	260.7	58
USGS 16725000	Alakahi	20.071	-155.671	7.3	52
USGS 16720000	Kawainui	20.085	-155.681	14.1	52

4.3.2 Gridding

Although implementing a 250m resolution estimation is preferred for more accurate results, the computation and iteration time for optimization is too significant. Therefore, two resolutions are combined: the high 250m resolution and a courser 5km resolution. This method takes into account the spatial variability of R, ET and ALU, while keeping the processing and evaluation at a reasonable level.

The coarser grid consists of 412 pixels at 5km resolution, or 25km^2 area, descending from North Kohala to Ka'ū (Figure 4-2). This grid is the baseline for both the data estimation and entropy-based land allocation optimization studies. The border pixels that consist of ocean and land are accounted for in the processing stage.

The high resolution meteorological and ALU data are aligned and clipped to their common features and are resampled to 250m when needed. After this up-scaling, crop categories such as taro and flowers are omitted since they have negligible contribution at 250m resolution. Macadamia, coffee, diversified crop, topical fruits, papaya, banana, commercial forestry and pasture are kept. All unclassified agricultural land is assumed to be non-crop. Dairy is also classified as non-crop.

In each 25km^2 pixel, the high resolution AET, RET and R datasets are averaged over each land-use component. By doing this type of evaluation, different types of crop and non-crop water requirements in each pixel are approximated more precisely since there are 400 sub-pixels within each 25km^2 pixel. The high resolution products

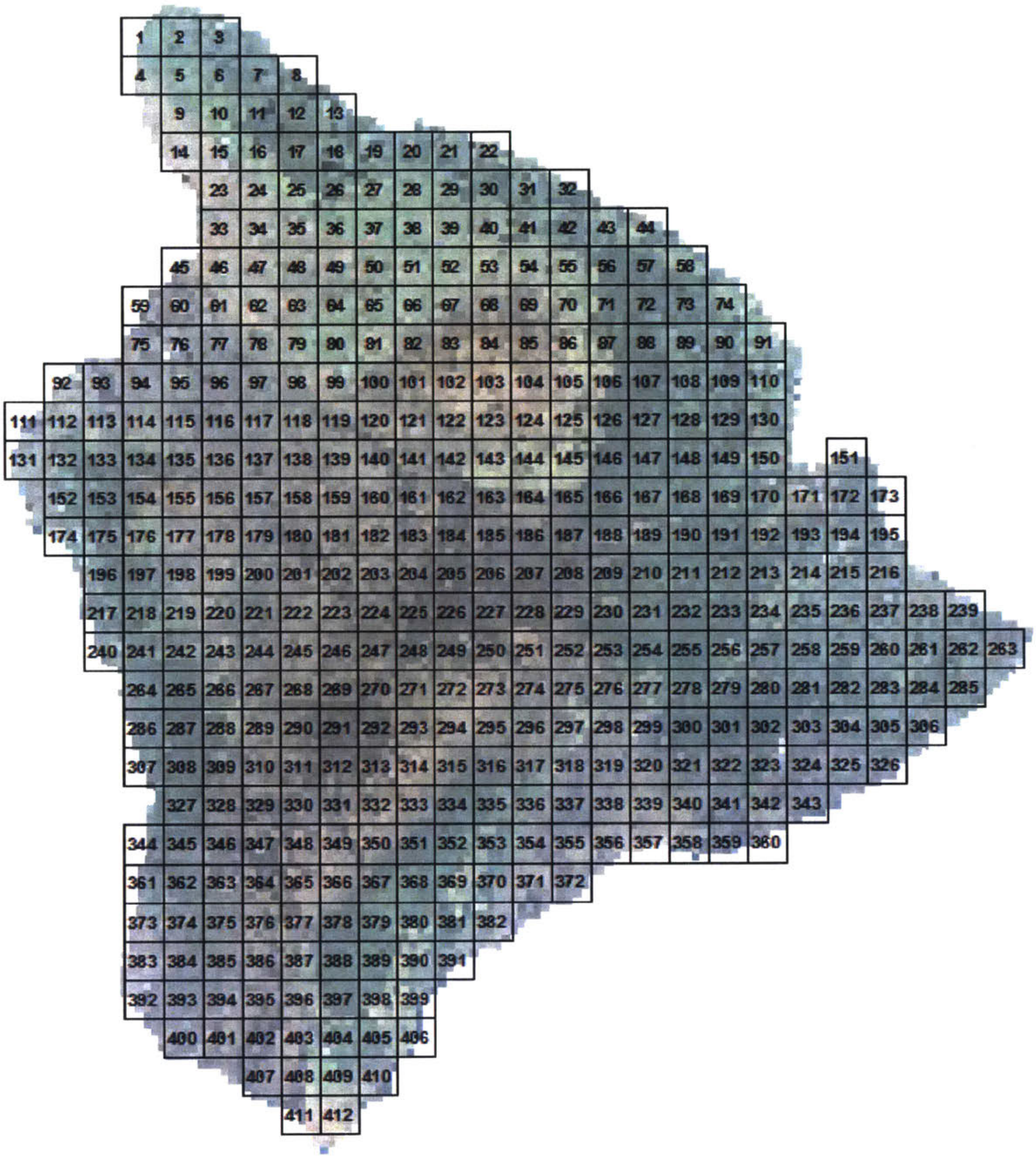

Figure 4-2: 5km Resolution General Grid. This is the general grid template that is used throughout both optimizations.

are therefore considered indirectly. An illustration of this process is displayed in Figure 4-3. The different colors in the land-use square represent vegetation types. R, RET and AET are averaged over the area associated with each vegetation type to obtain a higher resolution approximation.

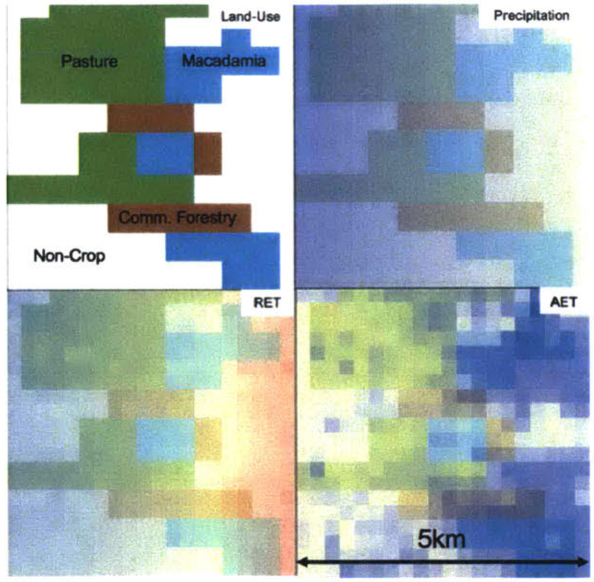

Figure 4-3: Pixel and Sub-Pixel Illustration. R, RET and AET sub-pixels are overlaid on the ALU then averaged over each ALU component to obtain more representative data for each pixel.

4.3.3 Flow Routing

The water balance constraint in the least-squares optimization requires information of lateral water movement from pixel to pixel. Flow routing provides this information by processing elevation gradients at each pixel and determining their respective sub-tributaries, ultimately providing a means to approximate the amount of water that is available in a given pixel per unit time. Because the control boundary in this evaluation includes both surface and groundwater flow, flow routing directions are assumed to hold for both.

Flow routing in Geographic Information Systems (GIS) utilizes digital elevation models (DEM) in tandem with national hydrology dataset (NHD) streamflow networks. This thesis uses DEM images that are prepared by the USGS The National Map. The finest Hawai'i Island DEM files consists of four merged 1/3 arc-second (approximately 10m) resolution raster images.

D8 Flow Directions

There are a few different types of direction standards for flow routing including D8, D-inf and multi-flow. D8 is used in this application, as it is the simplest method and most easily executed in GIS. In the D8 standard, water moves on the steepest slope to its nearest neighbor and exits the pixel in 1 of 8 directions. The result on a per pixel basis is numerical: 1, 2, 4, 8, 16, 32, 64 or 128, with each discrete number representing a specific direction. The directions and routing method are portrayed in Figure 4-4.

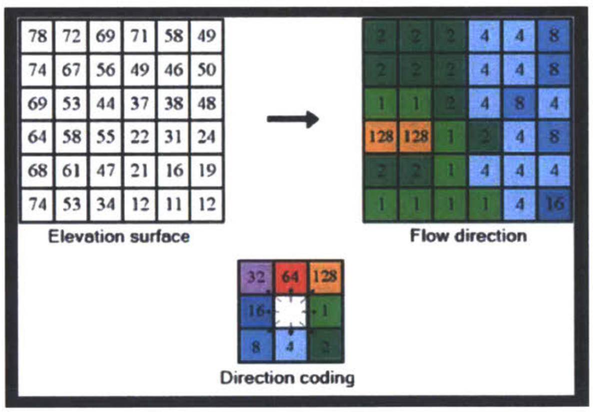

Figure 4-4: D8 Flow Routing Standard. Source: Esri

DEM Reconditioning and Up-Scaling

When routing on high resolution, it is often necessary to recondition a DEM using an NHD stream network to maintain an accurate and precise spatial approximation of recognized streams, bodies of water and outlets. Reconditioning is done by merging the stream network onto the DEM in GIS. Although there are globally routed models like Total Runoff Integrating Pathways (TRIP) (Oki et al., 1998) that do this, the resolution is too large for a focused study of Hawai'i. Therefore, it is integral in producing a routing scheme particularly for Hawai'i at the specific study resolution.

Figure 4-5 illustrates a reconditioned DEM flow routing scheme at 250m resolution. Note the intricacies of the stream network with the high resolution pixels. This yields a highly-precise configuration, in which the flow routing results capture the

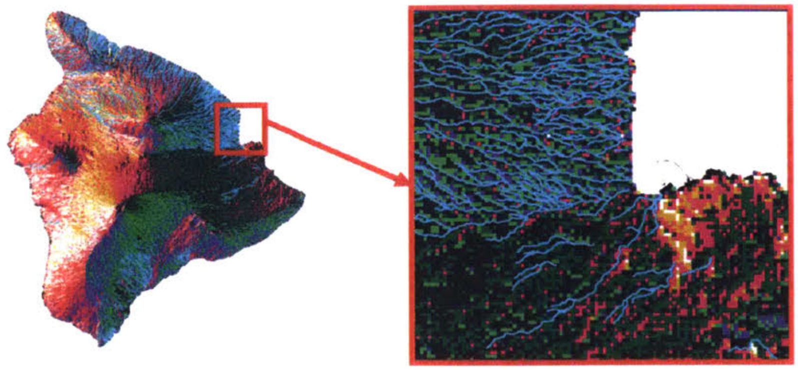

Figure 4-5: Flow Routing 250m Resolution. Different colors represent flow directions, cyan represents the stream network.

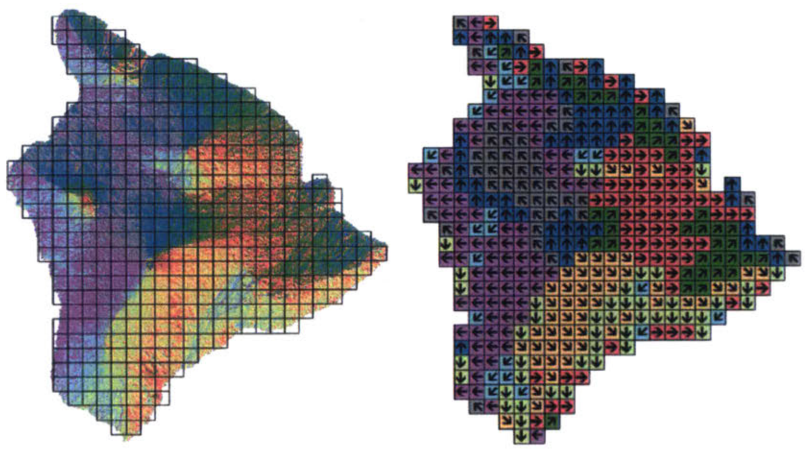

Figure 4-6: Comparing Flow Routing Resolution - Left: 250m, Right: 5km. Colors represent D8 directions and are kept consistent in both schemes

stream channels at the 250m resolution. If reconditioning was not done in this case, the pixels near the streams may have contradicted the direction of the surface water flow.

When up-scaling to a coarser resolution, processing the topographic effects to recognize North Hawai'i Island's complex stream network is infeasible due to the larger pixel size. Therefore, we assume that flow routing on an up-scaled DEM captures the major networks without reconditioning. This is seen in Figure 4-6, where the 5km resolution routing grid closely resembles that of the 250m grid.

4.4 Regional Zoning for Focused Estimation

In studies done prior (Smith, 2016; Figueroa, 2012), estimation of Kc factors for each crop are assumed to be constant over the entire study boundary. Initial estimated Kc coefficient without zonal features (assuming constant factors) were overestimated in the dry climate zones with porous lava rock/soil and were underestimated in the wetter climates with high clay content. Because of the wide variability in Hawaiian climate and soils, it is necessary to establish regional zones that correlate with the Island's physical setting.

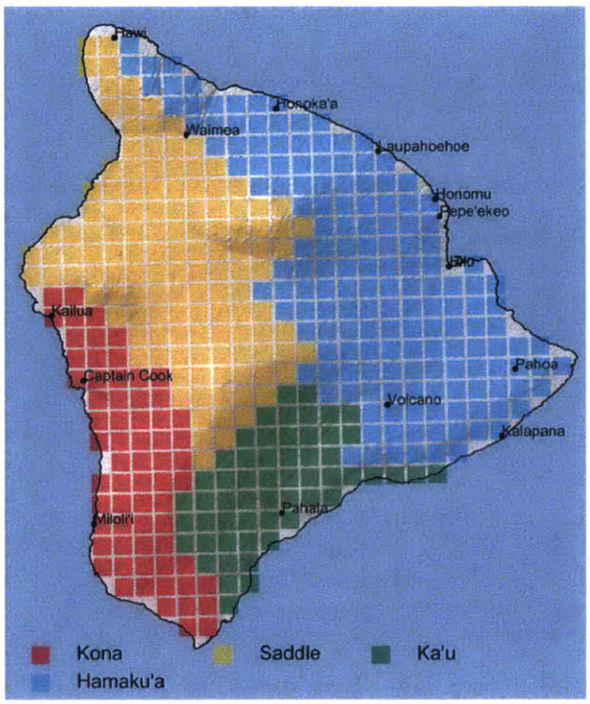

Figure 4-7: Assimilation Zones. Different colors represent delineated zones.

Four zones (set Ω_{zone}) are delineated (Figure 4-7), which are primarily characterized by rainfall and elevations of the region. The Saddle zone consists of the dry leeward land with the high elevations of Mauna Kea and Mauna Loa. In this region, porous volcanic material induces rapid infiltration. The Hāmāku'a zone captures the very wet windward slopes and old features of the Island. In this region, humidity and runoff is very high. The Kā'u and Kona zones are considered intermediate zones.

Figure 4-8 illustrates the comparison of AET for the different zones. It is apparent that there are considerable differences in these zones with their distribution centroids positioned at four distinct levels. These differences confirm and motivate the delineation of zones.

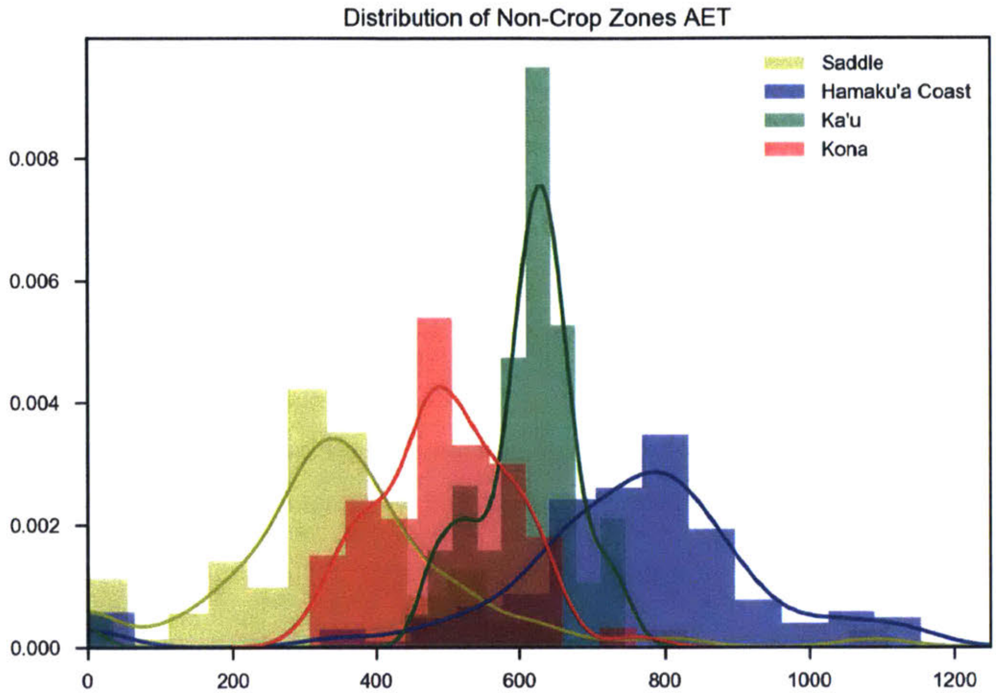

Figure 4-8: AET Distribution of Non-Crop

When comparing the non-crop AET to RET for different zones (Figure 4-9), it is apparent that the absolute differences between the medians of AET and RET are much larger for the Saddle zone than the Hāmāku'a zone. This validates the hypothesis that the coefficients vary substantially over each region and cannot be assumed constant over the entire Island for non-crop.

In the estimation, we assume commercial forestry, pasture and non-crop Kc coefficients change with zone. Other Kc coefficients such as those for papaya, banana and macadamia are uniform over the island. Although there may be zonal variation in ET, we assume these crops have adequate water (via irrigation) to transpire and function if rainfall water is limiting. Commercial forestry, pasture and non-crop are assumed to not be managed as well, and therefore have Kc coefficients that would

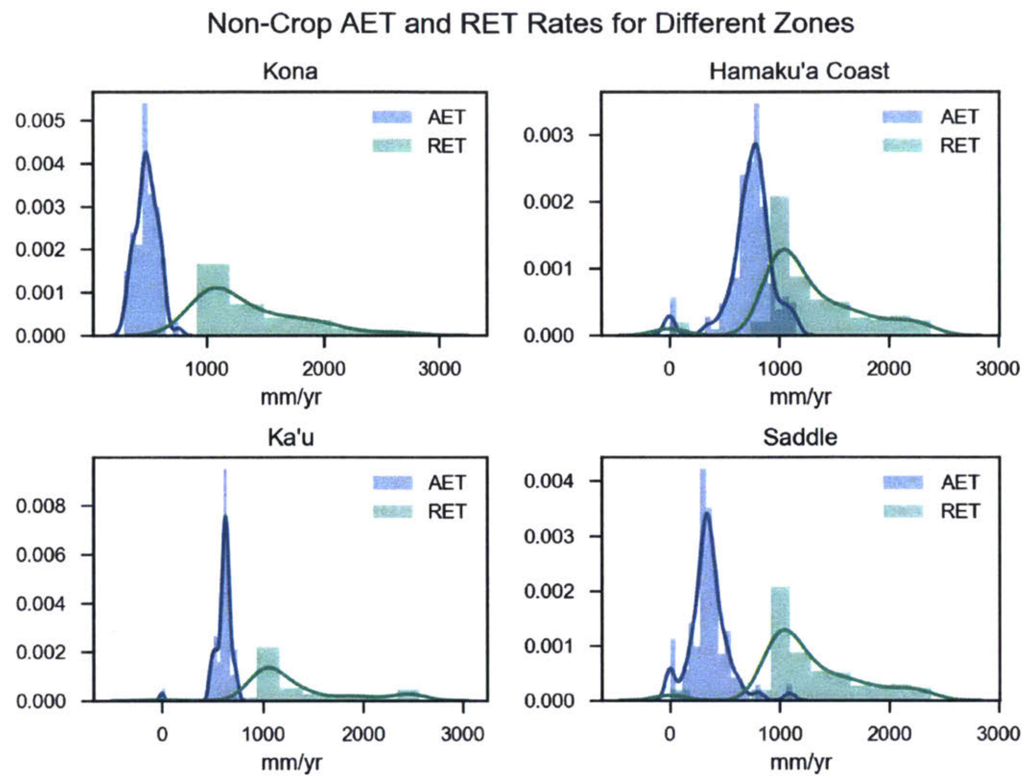

Figure 4-9: Distribution of Non-Crop AET vs. RET

vary considerably.

4.5 Results

The FAO Kc coefficients calculated from the resulting datasets are the important estimated products. Table 4.2 summarizes the FAO Kc coefficients. The entropy-based optimization in Chapter 5 directly implements the Kc factors into a water balance when assessing new crop allocations. Note that the coefficients of macadamia, coffee, diversified crop, tropical fruit, papaya and banana do not change with respect to region for reasons described above. Commercial forestry does not have coefficients available for the Saddle and Kona region because the ALU does not specify any commercial forestry in those zones.

Pasture and non-crop vary substantially with zone, which was anticipated when modifying the estimation to account for regional differences. Pasture and non-crop

Table 4.2: Estimated Kc_z Coefficients

Crop	Hāmāku'a	Saddle	Ka'ū	Kona
Macadamia	0.524	0.524	0.524	0.524
Coffee	0.495	0.495	0.495	0.495
Diversified Crops	0.472	0.472	0.472	0.472
Tropical Fruit	0.465	0.465	0.465	0.465
Papaya	0.445	0.445	0.445	0.445
Banana	0.430	0.430	0.430	0.430
Commercial Forestry	0.688	N/A	0.600	N/A
Pasture	0.577	0.189	0.269	0.265
Non-Crop	0.388	0.096	0.380	0.246

have the lowest coefficients in the Saddle zone, where there is rapid infiltration and less water lost as ET. Furthermore, the Hāmāku'a zone has the highest coefficient for pasture and non-crop. This was also hypothesized due to the older, more clayey soil and high potential for runoff.

Chapter 5

Entropy-Based Optimization

5.1 Overview

The objective of this thesis is to optimally allocate land and environmental resources with respect to Hawai'i Island's food agriculture, while taking into account the dramatic increase in number of small stakeholder farms and awareness of food self-sufficiency. A preliminary analysis found optimal allocation solutions for maximizing export revenue from cash crops subject to food self-sufficiency constraints. This analysis showed that Hawai'i Island is not fully using its agricultural resources. Although this simulation was formulated correctly, it did not represent realistic considerations and disregarded an important aspect in land-use planning for The State of Hawai'i. The optimizer created farms miles wide in uniformity with single crops. As a result, revenue and population far exceeded those of the current state of Hawai'i Island (and The State of Hawai'i), but constructed a landscape similar to the Plantation Era (Figure 3-1). From a mathematical point of view, the optimized solutions were feasible, but disregarded Hawaiian history, culture and values. To address this problem, it was essential to construct a new metric - entropy - that serves as a proxy for biodiversity, spatial heterogeneity and number of small stakeholder farms.

This chapter discusses the formulation and results of the entropy-based optimization. It concludes with a discussion of future considerations on how to further advance this research to provide a more in-depth analysis of agricultural land-use allocation.

5.2 Entropy-Based Approach

The entropy-based approach implements a modified or weighted version of Shannon entropy from information theory (Shannon, 1948). The weighted Shannon entropy is used as a metric for biodiversity and spatial heterogeneity, and in theory, captures the patterns of the current Island landscape with the given constraints. Non-crop, or wild vegetation, is assumed to be composed of many different types of vegetation, while crop varieties are represented as one each. Therefore, when evaluating entropy within a system or area boundary, non-crop regions are assigned high entropy while individual crop areas are considered low entropy (Figure 5-1).

With this type of modification, the optimization model favors wild vegetation, conservation and open space - fulfilling goals described in The State of Hawai'i Constitution, The Hawai'i 2050 Sustainability Plan, The Hawai'i County Development Plan and various Community Development Plans.

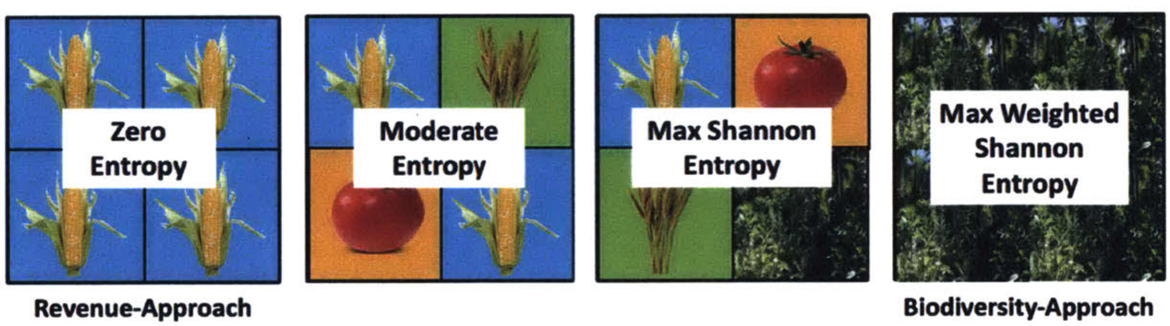

Figure 5-1: Shannon Entropy Diagram. Considering four different crop types of maize, wheat, tomato and non-crop, Shannon entropy is weighted such that all non-crop is the highest entropy.

Figure 5-1 illustrates the difference between optimizing export revenue and hence, maximizing mono-cropping systems, versus maximizing entropy, which favors native vegetation and biodiversity within the spatial extent.

5.3 Formulation

5.3.1 Objective Function

Optimization

The objective function maximizes a total weighted Shannon entropy (measured in bits) for the Island, subject to land, biophysical, population and water constraints. For each pixel, the entropy is calculated over the region of 8 surrounding pixels (or less depending on where the pixel is positioned) in addition to the pixel itself. For each calculation of pixel entropy, crop and non-crop terms are partitioned and weighted by their respective ratio of area to total boundary area. This partitioning is essential to properly represent vegetation diversity in non-crop areas.

With this modified formulation of Shannon entropy, the objective function effectively captures crop and landscape diversity by maximizing non-crop area and dispersing food crops over available agricultural land. Additional weights are appended in order to penalize for larger cropping areas and award for more non-crop areas.

Equation 5.3 expresses the weighted crop entropy summed over all crops and pixels. Equation 5.4 expresses the weighted non-crop entropy summed over all pixels. The objective function (Equation 5.2) adds both weighted entropy terms together and is maximized for each simulation.

$$\hat{u} = \underset{\{u\}=\{\bar{A}^{(c)},\bar{A}^{(nc)}\};\, c\in\Omega_{crop}}{\arg\max} J(Q_1, Q_2) \tag{5.1}$$

$$J(Q_1, Q_2) = Q_1 + Q_2 \tag{5.2}$$

$$Q_1 = -\sum_{p\in\Omega_{grid}} \left(\frac{1}{\alpha} \frac{\sum_{c\in\Omega_{crop}} \bar{A}_p^{(c)}}{\bar{A}_p^{(T)}} \sum_{c\in\Omega_{crop}} \left(\frac{\bar{A}_p^{(c)}}{\bar{A}_p^{(T)}} log_2 \frac{\bar{A}_p^{(c)} + \delta}{\bar{A}_p^{(T)}} \right) \right) \tag{5.3}$$

$$Q_2 = -\sum_{p\in\Omega_{grid}} \left(\alpha \frac{\bar{A}_p^{(nc)}}{\bar{A}_p^{(T)}} \left(\eta \left(\frac{\frac{\bar{A}_p^{(nc)}}{\eta}}{\bar{A}_p^{(T)}} log_2 \frac{\frac{\bar{A}_p^{(nc)}}{\eta} + \delta}{\bar{A}_p^{(T)}} \right) \right) \right) \tag{5.4}$$

$$\bar{A}_p^{(c)} = \sum_{n\in\Omega_{comp(p)}} A_n^{(c)}; \quad \bar{A}_p^{(nc)} = \sum_{n\in\Omega_{comp(p)}} A_n^{(nc)}; \quad p \in \Omega_{grid},\, c \in \Omega_{crop}$$

$$\bar{A}_p^{(T)} = \Big(\sum_{c\in\Omega_{crop}} \bar{A}_p^{(c)}\Big) + \bar{A}_p^{(nc)}; \quad p \in \Omega_{grid}$$

Where, $J(Q_1, Q_2)$ is the objective function, which is maximized with vector $\hat{u}$ spanning $\mathbb{R}^{\Omega_{crop}+1}$,

Q_1 is the weighted crop entropy function,

Q_2 is the weighted non-crop entropy function,

$\bar{A}_p^{(c)}$ is the estimated area of crop c in the 8 (or less) surrounding pixels of pixel p and pixel p,

$\bar{A}_p^{(nc)}$ is the estimated area of non-crop in the 8 (or less) surrounding pixels of pixel p and pixel p,

$\bar{A}_p^{(T)}$ is the total area of all crops and non-crop in the 8 (or less) surrounding pixels of pixel p and pixel p,

$A_n^{(c)}$ is the estimated area of crop c in pixel n and

$A_n^{(nc)}$ is the estimated area of non-crop in pixel n.

α is an extra weighting term to ensure maximum entropy in non-crop,

η is the partitioning term that divides non-crop into many types of vegetation and

δ is a small number that prevents 0 in the *log*.

Ω_{grid} is the set of all pixels in the computational grid,

Ω_{crop} is the set of considered crops and

$\Omega_{comp(p)}$ is the set of surrounding pixels and pixel p for pixel p.

5.3.2 Area Balance and Suitability Constraints

Pixel Area Balance

Most areas within the pixels span 25km^2, while others near the shoreline have less. Equation 5.5 expresses an area balance for the crop and non-crop areas within each pixel, indicating that these areas must sum to the total area within the pixel.

$$\Big(\sum_{c\in\Omega_{crop}} A_p^{(c)}\Big) + A_p^{(nc)} = A_{p_{max}}; \quad p \in \Omega_{grid} \tag{5.5}$$

Where, $A_p^{(c)}$ is the estimated area of crop c in pixel p,

$A_p^{(nc)}$ is the estimated area of non-crop in pixel p and

$A_{p_{max}}$ is the area of land in pixel p.

Ω_{grid} is the set of all pixels in the computational grid and

Ω_{crop} is the set of considered crops .

Non-Crop Area Constraint

The total Island landscape is generalized into three main categories: unavailable lands, available crop lands and available non-crop lands. Unavailable lands represent the current macadamia and coffee farms as well as the pastureland, recognized reserves and a fraction of the current commercial forestry. Available crop lands are considered lands that are open for cultivation, including present cropland and land that is suitable for crops. Available non-crop, or wild vegetation, is everything else - land that is not being cultivated, but is available for agricultural expansion. In order to quantify the expansion of agriculture and the tradeoff between population and entropy, fractions of available non-crop lands closed to agriculture are varied, where 0% is maximum agricultural expansion (all available non-crop lands are opened to agriculture) and 100% is the current agricultural land-use of Hawai'i Island (all available non-crop lands are closed to agriculture).

$$\sum_{p \in \Omega_{grid}} A_p^{(nc)} \geq \mu \sum_{p \in \Omega_{grid}} \tilde{A}_p^{(nc)} \tag{5.6}$$

Where, $A_p^{(nc)}$ is the estimated area of non-crop in pixel p and

$\tilde{A}_p^{(nc)}$ is the existing area of non-crop in pixel p.

μ is the varying scalar parameter that ranges from 0% to 100%.

Ω_{grid} is the set of all pixels in the computational grid.

Crop Suitability Constraint

Within each pixel is a suitability constraint for each crop. Suitable area is expressed as a fraction of the total pixel area. This is because suitability is evaluated on a finer scale than the general grid pixel size. Equation 5.7 constrains the upper bound area of each crop to its suitable area in each pixel. Suitability of pasture and commercial forestry is their current respective areas and cannot expand. Non-crop is assumed to be suitable over the entire Island. Suitability parameters are taken from Sys et al. (1991) and FAO EcoCrop (EcoCrop, 2000) and include rainfall, temperature, altitude, slope, soil depth, cation exchange capacity, pH, organic carbon and electrical conductivity. For suitability maps, refer to A-3 to A-14. Gridded soil parameters are obtained from the USDA National Resource Conservation Service (NRCS).

$$A_p^{(c)} \leq A_{p_{suit}}^{(c)}; \quad p \in \Omega_{grid} \tag{5.7}$$

Where, $A_p^{(c)}$ is the estimated area of crop c in pixel p and
$A_{p_{suit}}^{(c)}$ is the suitable area of crop c in pixel p.
Ω_{grid} is the set of all pixels in the computational grid.

Additional Area Constraints (Unavailable Lands)

In addition to the pixel area balance, we carefully considered which types of land should remain unchanged from present land-use data. In this optimization, all current pastureland in addition to macadamia and coffee farms are kept constant. Furthermore, commercial forestry is constrained to at least 80% of its current levels and larger residential areas such as Hilo, Kona, Hōnōka'a, Waimea and Hawi are removed from agricultural expansion. Finally, all reserves, as defined by the Department of Land and Natural Resources (DLNR), including historical parks, bird sanctuaries and military lands are also removed from any agricultural expansion consideration. Reserve areas are classified as unavailable non-crop areas. For the map of these unavailable lands, refer to A-1.

5.3.3 Population and Diet Constraints

Population and Diet Constraints

In order to determine how many people can be fed with locally produced crops (people self-sufficient), a diet is formulated using the U.S. Department of Health (DOH) and U.S. Department of Agriculture (USDA) 2015-2020 dietary guideline book. We assume that the average Hawai'i resident eats 2400cals/day. From this caloric assumption, a factorized diet in terms of vegetables and fruits is derived using the "Healthy U.S.-Style Eating Pattern" as defined by the DOH and USDA. Note that protein, dairy, oils and grains are not added into the diet due to limitations on time and data. Therefore, the calculation is for population of people self-sufficient in fruits and vegetables.

Yield data is used to calculate the total production of cash and food crops. Yield statistics are gathered from the latest 2011 USDA NASS. When available, yield is averaged over 5 years from 2007 to 2011 for all crops. In addition, when available, yield recorded by the County of Hawai'i Island is used over the average yield recorded for The State of Hawai'i. Data for this is tabulated in Table 5.1.

$$1.5PS^{(c)} = \Big(\sum_{p \in \Omega_{grid}} A_p^{(c)} \Big) Y^{(c)}; \quad c \in \Omega_{crop} \tag{5.8}$$

Where, P is the minimum population that is food self-sufficient in fruits and vegetables and is a varying parameter in the optimization model,

$S^{(c)}$ is the per capita annual consumption of crop c,

$A_p^{(c)}$ is the estimated area of crop c in pixel p and

$Y^{(c)}$ is the average yield for crop c.

Ω_{grid} is the set of all pixels in the computational grid and

Ω_{crop} is the set of considered crops.

Note Equation 5.8 is multiplied by 1.5 on the left, which assumes that 50% of production is lost pre- and post-harvest.

5.3.4 Water Balance Constraints

The water balance constraints are similar to those used in Chapter 4, but utilize the Chapter 4 estimated Kc coefficients to obtain a more representative balance for the potential scenarios of cropland allocation. The estimation analysis is based on 250m resolution grid cells. Due to an up-scaling in the entropy-based optimization, the crop evaporation coefficients are allowed to vary ±25% to account for a slight margin of error. Because crop water requirements are estimated on the basis of diversified crops and tropical fruits and not the individual types of vegetation, all vegetables are assumed to be under the diversified crop domain, while avocado is under tropical fruit. Macadamia, coffee, banana, commercial forestry, pasture and non-crop use their own respective estimated evaporative coefficients. Data for this is tabulated in Table 5.1. With regard to environmental resources, levels of runoff and groundwater flow are kept at the current estimated levels.

Table 5.1: Vegetation Information. D.C. is Diversified Crops, T.F. is Tropical Fruits (as defined by ALU), Unique indicates that that vegetation type has its own Kc coefficient from the estimation in Chapter 4, N/A means that there is no data available or the data is not relevant to the study.

Vegetation Type	Kc_z Coefficient	Yield (000lb/acre)	Serving (kg/person-year)
Celery	D.C.	19.20	12.5
Cucumber	D.C.	11.65	8.3
Eggplant	D.C.	19.16	4.3
Lettuce	D.C.	11.60	25.0
Onion	D.C.	12.40	4.2
Sweet Potato	D.C.	14.92	30.6
Tomato	D.C.	19.30	19.2
Broccoli	D.C.	4.00	9.6
Avocado	T.F.	2.62	7.5
Banana	Unique.	17.18	6.1
Macadamia	Unique	2.96	N/A
Coffee	Unique	1.32	N/A
Commercial Forestry	Unique	N/A	N/A
Pasture	Unique	N/A	N/A
Non-Crop	Unique	N/A	N/A

5.4 Results and Discussion

In the optimization model, fraction of available non-crop closed to agriculture and self-sufficient population parameters are varied (μ in Equation 5.6 and P in Equation 5.8) while entropy is maximized, resulting in an optimal region in a 3-dimensional subspace. The fraction μ is varied from 100% to 0%, where 100% means that all current lands that are classified as available non-crop cannot be considered for cultivation and 0% opens all available non-crop lands to agriculture. Available non-crop lands are defined as all non-crop land less unavailable non-crop land, which include reserves, military bases, major towns, etc. The number of people self-sufficient P is initialized at 0 people and increases until the optimization model cannot find a feasible solution. The optimal region derived from the parametric analysis for this study is displayed as a Pareto tradeoff curve in Figure 5-2.

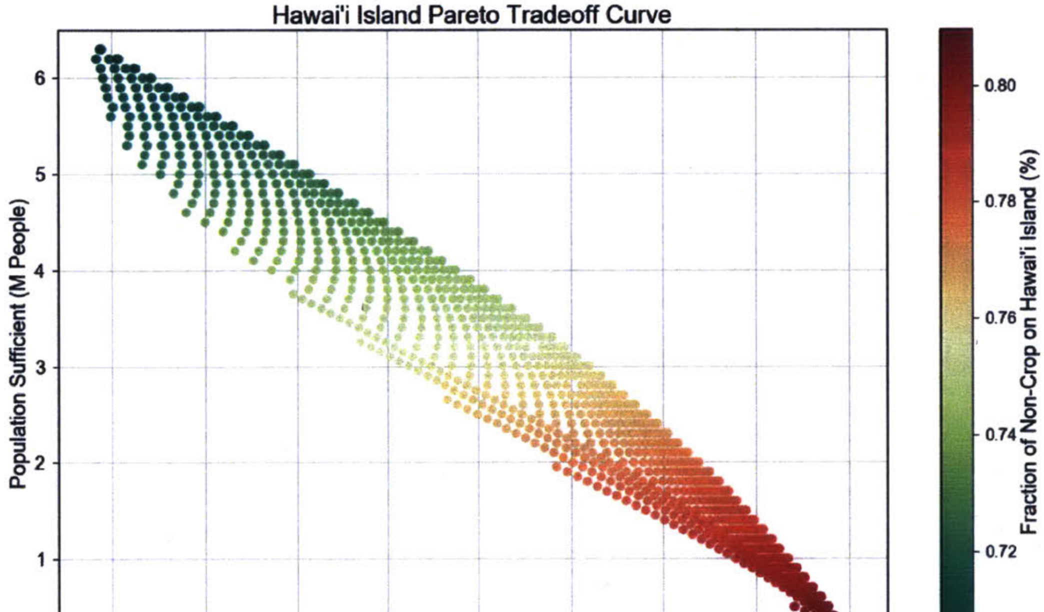

Figure 5-2: Pareto Tradeoff Curve. Result produced from the entropy-based optimization by varying self-sufficient population and fraction of non-crop closed to agriculture.

All points in Figure 5-2 represent a feasible optimal solution that meets the self-sufficient population requirement and maximizes spatial heterogeneity given a defined amount of non-crop land available for agricultural expansion. Note that the fraction of non-crop on Hawai'i Island is not the same as fraction of available non-crop closed to agriculture μ.

As self-sufficient population increases, more non-crop land needs to be unlocked for agricultural expansion. The opening of available non-crop lands, as illustrated from red to green, is required to satisfy the increase in self-sufficient population. At low self-sufficient populations, approximately 20% of Hawai'i Island is used for agriculture[1]. This is consistent with the current landscape as estimated by the USDA.

The results show that, if done right, Hawai'i Island could provide 300,000 people with sufficient fruits and vegetables in the specified crop categories, while maximizing heterogeneity of the current landscape. Around 10% more available non-crop land of the total Hawai'i Island would need to be accessed to sustain 6M people. Note that the optimization is initialized at approximately 82% non-crop (and not 100%). This is because the current extents of pasture, macadamia and coffee are kept unchanged and commercial forestry is kept to at least 80% of its current extent throughout the optimization process. These three agricultural landscapes are relatively significant in North, West and Southeast Hawai'i Island.

The entropy axis is high when the self-sufficient population is low and fraction of non-crop area on Hawai'i Island is high. With high fraction of non-crop area or wild vegetation, the entropy is large due to the higher biodiversity and spatial heterogeneity in the pixel boundaries. However, as population increases, more land is allocated to cropping, removing wild vegetation and reducing spatial heterogeneity and ecological biodiversity.

Figure 5-3 depicts entropy heat maps if 50% of available non-crop land is accessible for farming. The heat maps show a visual representation of Figure 5-2 and illustrate the decrease in overall Island entropy as cropland expands in response to an increase in self-sufficient population. These areas are especially sensitive in the places where cropping is already happening such as in Kona, Hawi, North Hilo, Puna and Ka'ū.

[1]This includes land allocated for cash crops, food crops, pasture and commercial forestry.

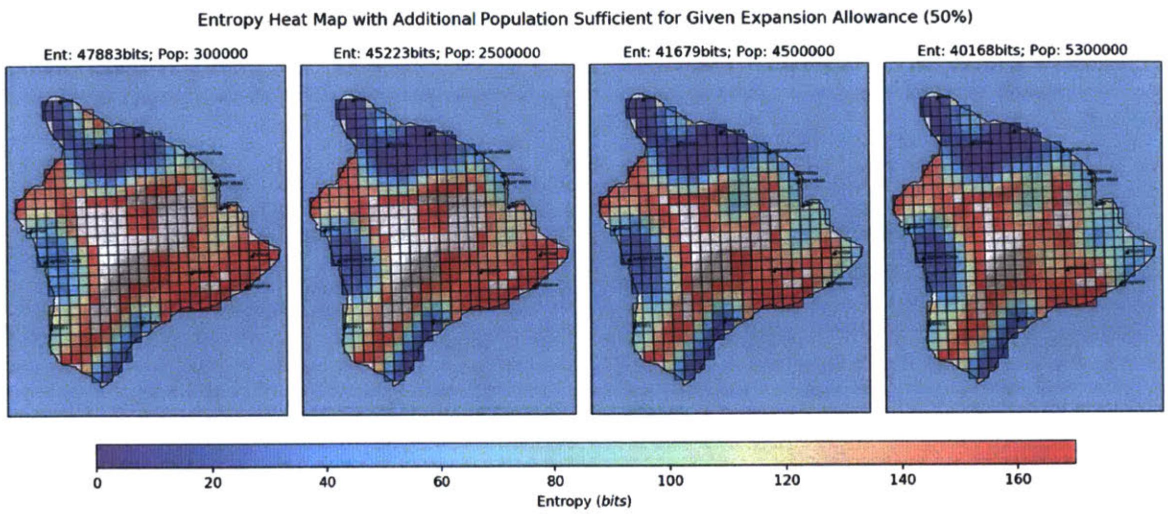

Figure 5-3: Focused Entropy Heat Maps with Progression in Population. Titles for each heat map display the total island entropy Ent and the self-sufficient population Pop. Pixels not colored have entropy levels that are numerically maxed with respect to non-crop. These particular scenarios allow cropland to expand to 50% of the total available non-crop areas presently delineated.

Major reasons why the optimization model intensifies cropping in these areas are biophysical suitability and water balance constraints, which are favorable for more crops. Furthermore, available non-crop land is concentrated in these areas where the large plantations used to be.

Note that the summit of Mauna Kea has entropy relating to agriculture only because the surrounding pixels have crop uniformity. Much of this has to do with the substantial pastureland in Kohala and Waimea, which is represented by the large low entropy (purple) region.

To gain a better understanding of the mechanisms behind entropy and to compare the two extreme scenarios of high and low population with respect to cropland allocation, Figure 5-4 and Figure 5-5 display the optimization model's crop allocation for selected pixels at high and low self-sufficient population values.

In Figure 5-4 and Figure 5-5, it is apparent that the maximization of entropy favors diversity in the pixels. For the most part, the low population (300,000 people) scenario has a lot of non-crop and pasture areas in the selected pixels, which reflect the current landscape of the Island. Macadamia, coffee and commercial forestry are in the pixels because these crops are constrained. In the simulation of 300,000 people, no crops are grown in the 6 particular pixels.

For the high self-sufficient population case (5,3000,000 people), the optimization model removes a large portion of non-crop area, as is reflected by the larger percentages of cropland in the middle of the pie charts, the smaller areas of orange (land area) in the pie charts and the change in color (entropy) of the pixels. With the decrease in non-crop land, food crops are added, but in the most diversified manner. This type of allocation - in which almost all crops are present but over relatively small areas - is the result of the weighted entropy objective function (Equation 5.1), which penalizes for mono-cropping.

The population-diversity tradeoff is seen from the removal of non-crop lands and a decrease in ecological and spatial diversity, but an increase in self-sufficient population. For this particular scenario, all crop and non-crop areas per pixel are tabulated from A-18 to A-28. Note that Pixel 194 in Figure 5-5 does not change in landscape, but changes in entropy. This is due to the calculation of Shannon entropy over the boundary of the pixel rather than just the pixel itself. With this formulation, the optimization model takes into account the effect of mono-cropping in the surrounding areas.

The tradeoff between self-sufficient populations and farm area is comprehensively shown in Figure 5-6, which displays the IQR statistics of farmland dedicated to the selected fruits and vegetables with changes in population if 50% of the available non-crop lands are opened for agricultural expansion. Note that Figure 5-6 projects statistics of farmland area per 25km^2 pixels and not statistics of individual farms.

At a low population, there are relatively small farms that are as dispersed as much as possible throughout the Island. As population increases, farms get larger and replace wild vegetation, which result in lower entropy and higher changes in physical landscape. Note that macadamia and coffee do not vary with population since they do not contribute to the characterized diet.

Between 2007 and 2012, the USDA Census reported Hawai'i Island to have approximately 4280 to 4650 farms, respectively, with an average farm in the range of

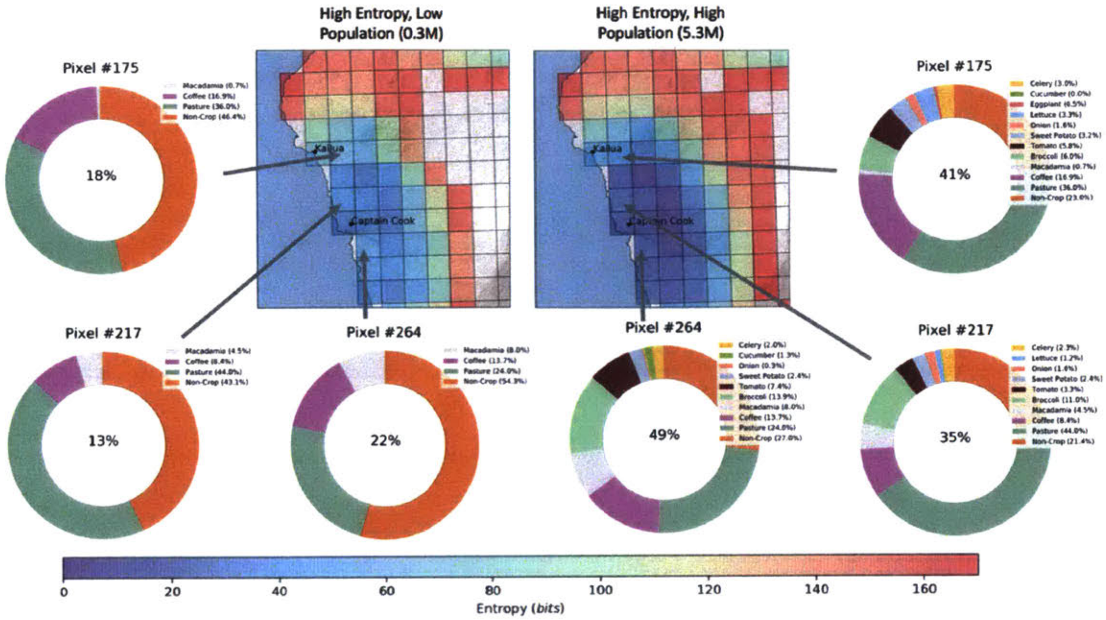

Figure 5-4: Focused Entropy Progression of Kailua Kona. The pieces of the pie charts represent the fractions of crop/non-crop area in the pixels. The percentages in the middle of the pie charts represent the percent of cropland in the pixels (excluding pasture and non-crop). These particular scenarios allow cropland to expand to 50% of the total available non-crop areas presently delineated.

0.59 to 0.65km^2 (147 to 160 acres). The distribution of farmlands (A-2) are highly skewed right, with about 60% of the farms ranging from 1 to 9 acres. To keep in accordance with the mindset of Hawai'i and to approach this problem appropriately, it is essential for agricultural planners to evaluate the tradeoff between farm size and self-sufficient population. In some regions at a very high population, cropland would need to be more than doubled, which would undoubtedly alter both ecological diversity and accessible lands (Figure 5-4 and Figure 5-5). It is clear that substantial increases in farmland will be needed to sustain a few million people, which may not be feasible or desired.

5.5 Conclusion

This thesis describes a multifaceted optimization model, which directly promotes spatial heterogeneity as a proxy for biodiversity and wild vegetation. Multilevel ben-

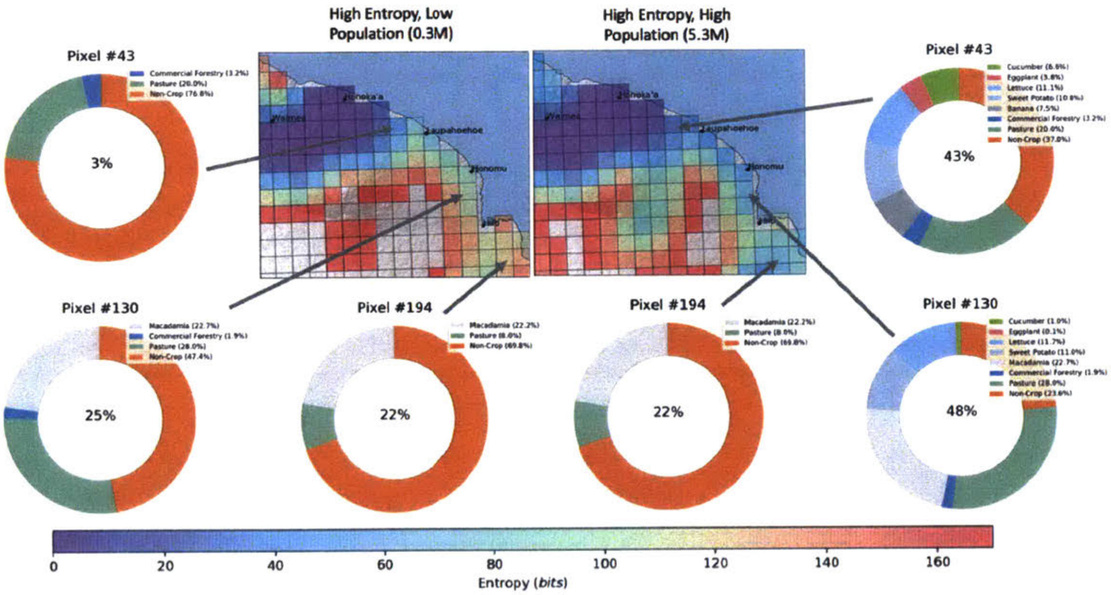

Figure 5-5: Focused Entropy Progression of North Hawai'i. The pieces of the pie charts represent the fractions of crop/non-crop area in the pixels. The percentages in the middle of the pie charts represent the percent of cropland in the pixels (excluding pasture and non-crop). These particular scenarios allow cropland to expand to 50% of the total available non-crop areas presently delineated.

efits from microbial, plant and soil functions to recreational, wildlife and ideological goals as well as historical trends are main reasons as to why biodiversity is directly implemented into the objective function. A modified version of Shannon entropy from information theory quantifies "diversity" and "openness" by effectively penalizing large plots of mono-culture farms that would be ecologically risky, economically unstable and presumably closed off to the public. By implementing entropy and population constraints, large plots of macadamia, coffee or other cash crops as well as industrialized farms are not favored, therefore producing a landscape that simultaneously supports Hawai'i Island's transition to small stakeholder farms and awareness of food self-sufficiency.

A key result of this thesis is a 3-dimensional Pareto tradeoff region, which presents various optimal allocations with different population constraints and areas of agricultural land available. The Pareto region identifies the potential of Hawaiian agriculture if Hawai'i were to truly push for food self-sufficiency.

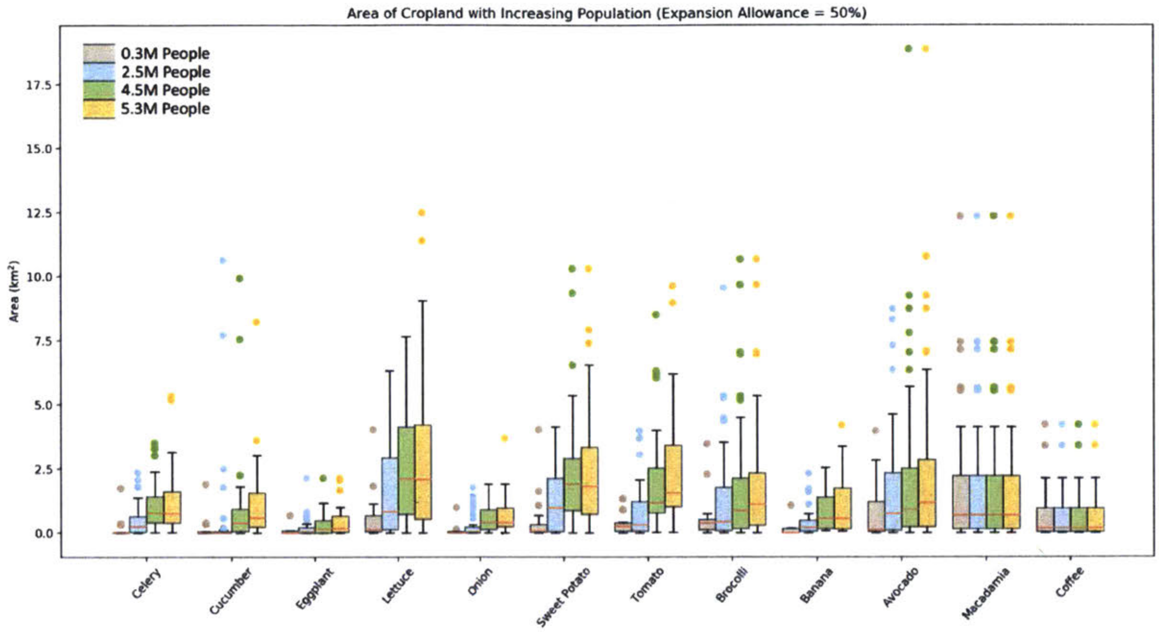

Figure 5-6: Cropland Area Statistics with Increasing Self-Sufficient Population. Cropland statistics from the optimization model's allocation if fraction of available non-crop closed to agriculture is set to 50% and self-sufficient population varies. The colors represent a different self-sufficient population.

It is seen from the entropy heat maps that an expansion of food self-sufficiency would surely create a more uniform landscape. This may be ecologically and economically undesired as well as unfavorable to the local people. Planners must be careful when deciding what point on the optimal region is most effective and favorable. This entails evaluating sizes of farms in pixels and identifying when the average farm size becomes too large.

The entropy-based optimization for Hawai'i is formulated to best represent Hawaiian agriculture and history. However, limitations arise when deciding which type of entropy/heterogeneity equation is most effective, as there are many different characterization metrics defined in literature (e.g. Li and Reynolds, 1994; Gustafson, 1998). More factors to take into account are the actual perimeter or aerial extent of homogeneity or the measurement of categorical aggregation of crops, which Shannon entropy does not directly address. A solution for this is to work with smaller pixel areas and map individual farms with discrete regions rather than fractions and/or to implement uncorrelated heterogeneity metrics that complement Shannon entropy.

Modifying Shannon entropy with weighting functions is a good way to approach a penalizing/awarding objective, but must be looked at further in a sensitivity analysis to decide what weights are best to use. In this analysis, non-crop area is always assigned higher entropy than crop area.

This thesis includes 14 different types of crop categories and non-crop. Pasture, coffee and macadamia are assumed unchanged and commercial forestry is kept to at least 80% of its current level. The other 10 crops are considered food crops and are selected because of the availability of data including suitability, yield, dietary function, etc. To expand this research, more crops should be added with appropriate data, particularly focusing on crop suitability parameters from local scientific and expert knowledge. Obtaining robust suitability data would substantially increase the accuracy of the optimization, as a preliminary sensitivity analysis has shown that suitability greatly defines the optimization outputs. Furthermore, a time-variant model can be formulated to include crop rotations and seasonality effects as this thesis looks at one crop per year. Protein from livestock as well as aquaculture can also be addressed in the optimization model.

As Hawaiian agriculture transitions to smaller stakeholder farms, maintaining wild vegetation, open lands, spatial heterogeneity and ecological biodiversity is important both scientifically and culturally. Optimally allocating land and environmental resources to increase food self-sufficiency is insufficient without consideration and sensitivity of the mono-cropping plantation history. It is more important than ever to quantitatively approach this multidimensional problem and to make calculated decisions that take into account the past, present and future. The government, communities, organizations and people must come together and set words to actions while learning from the past and moving forward to sustain Hawai'i in the most realistic and representative way.

Appendix A

Figures

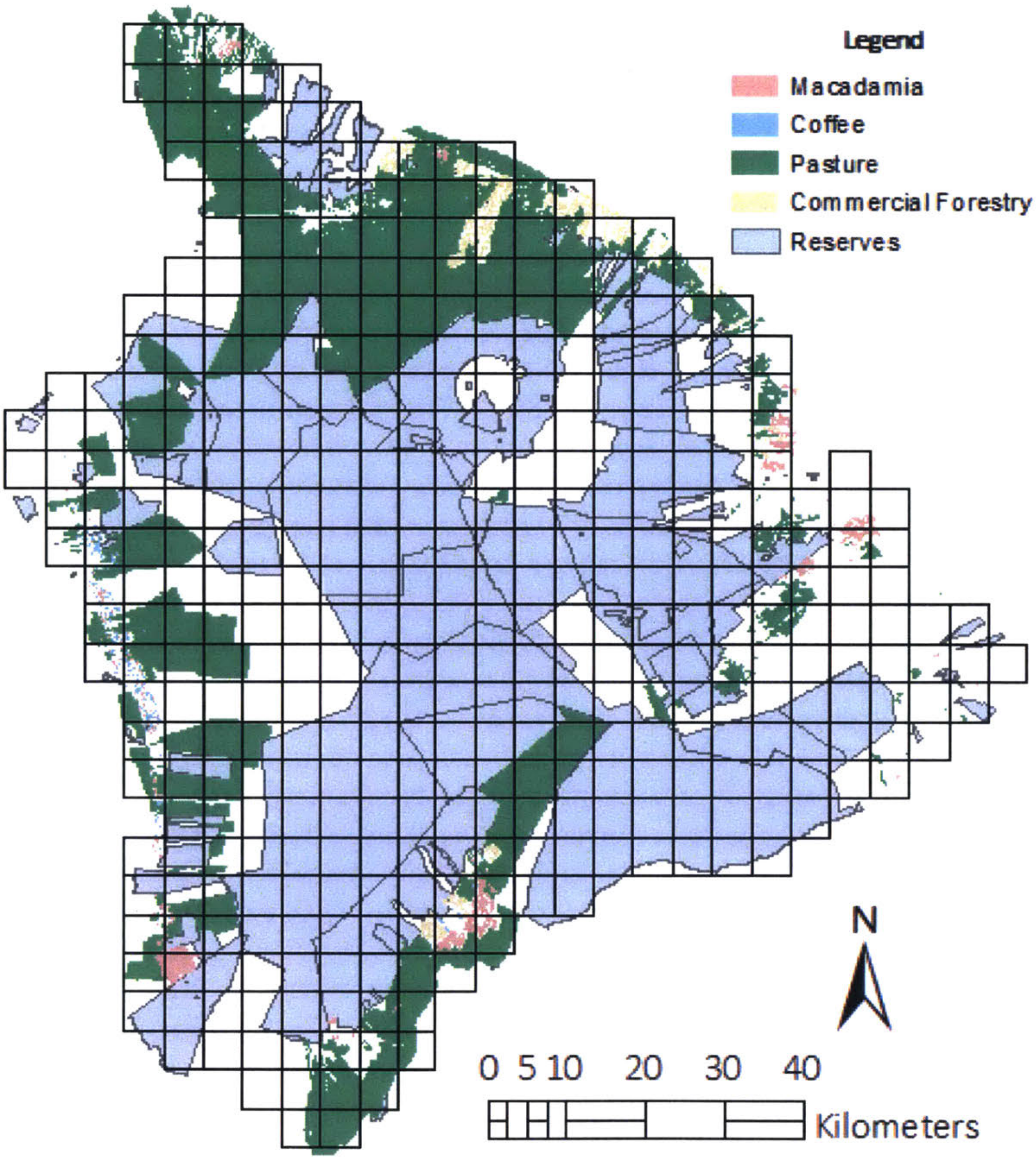

Figure A-1: Reserves, Pasture, Commercial Forestry, Macadamia Nut and Coffee Lands. These areas are kept at their current levels in the optimization model.

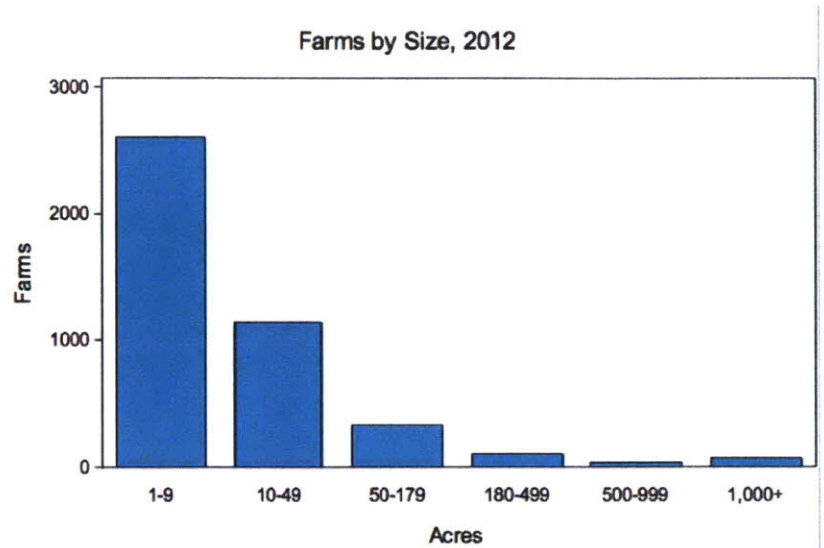

Figure A-2: Farmland Area Distribution (2012). Source: USDA NASS

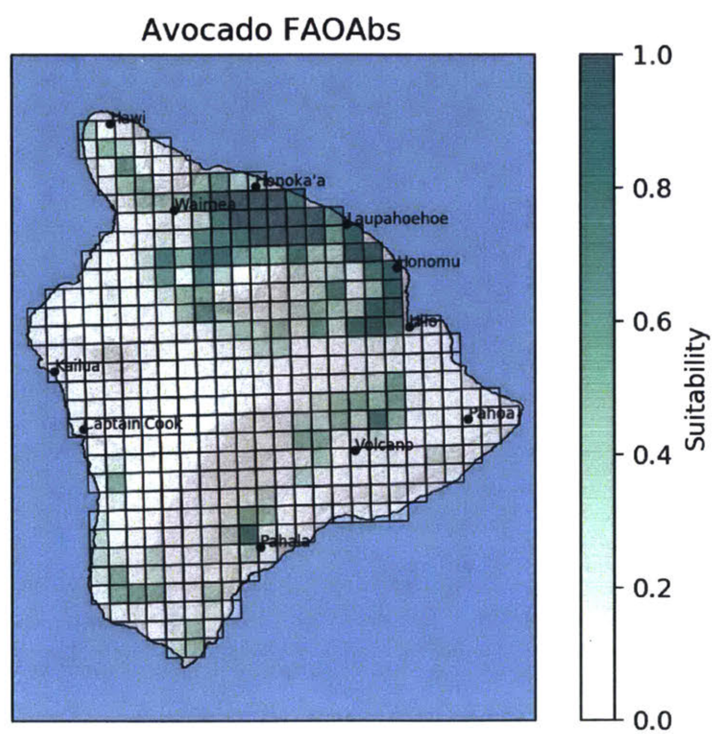

Figure A-3: Avocado Suitability

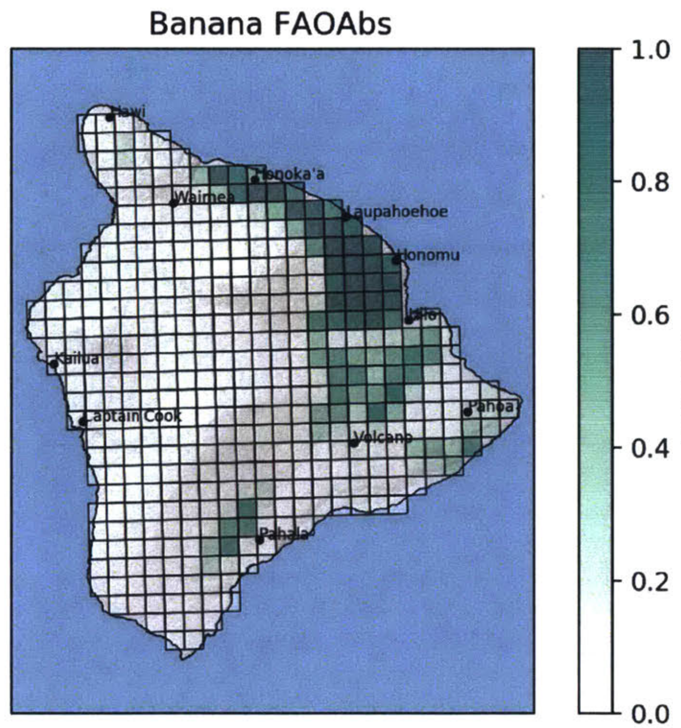

Figure A-4: Banana Suitability

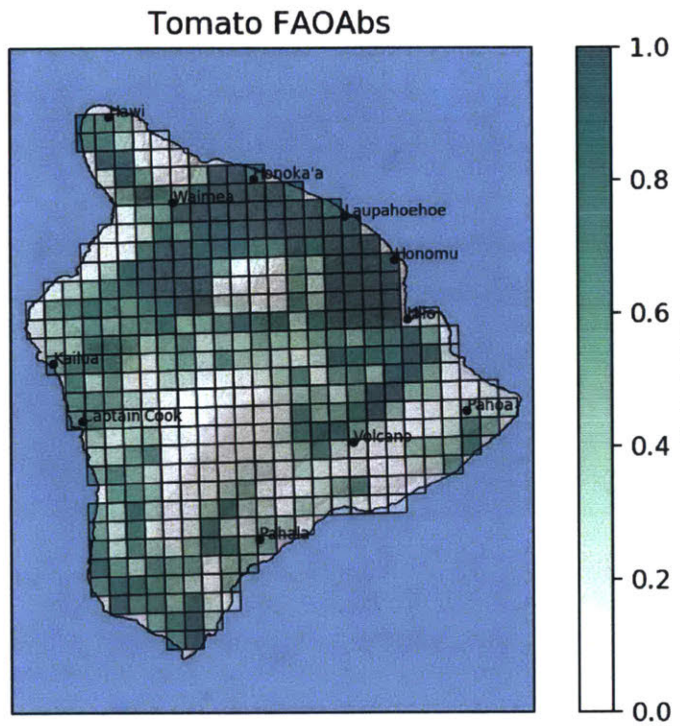

Figure A-5: Tomato Suitability

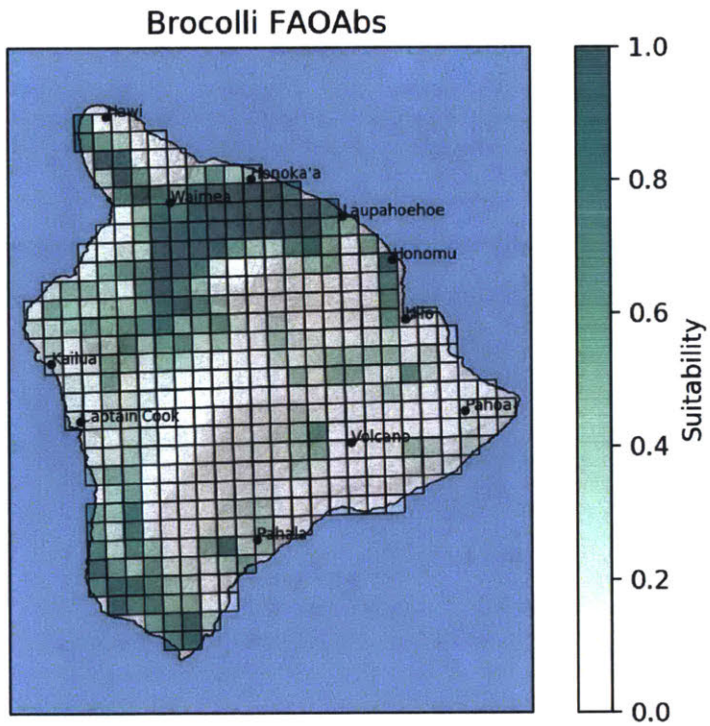

Figure A-6: Brocolli Suitability

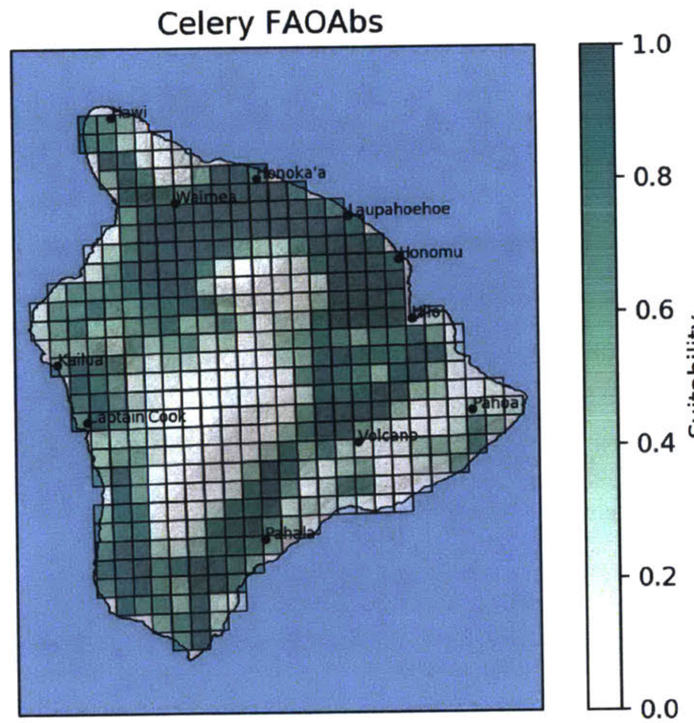

Figure A-7: Celery Suitability

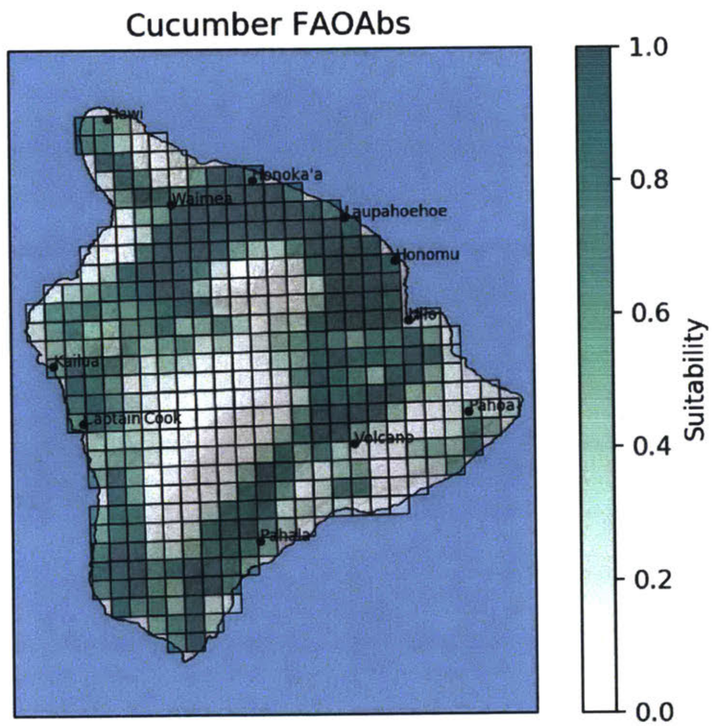

Figure A-8: Cucumber Suitability

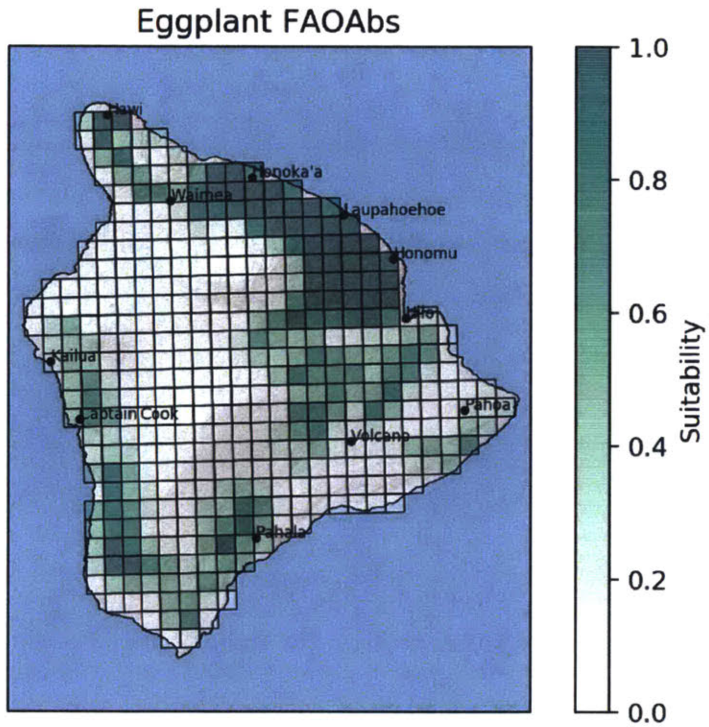

Figure A-9: Eggplant Suitability

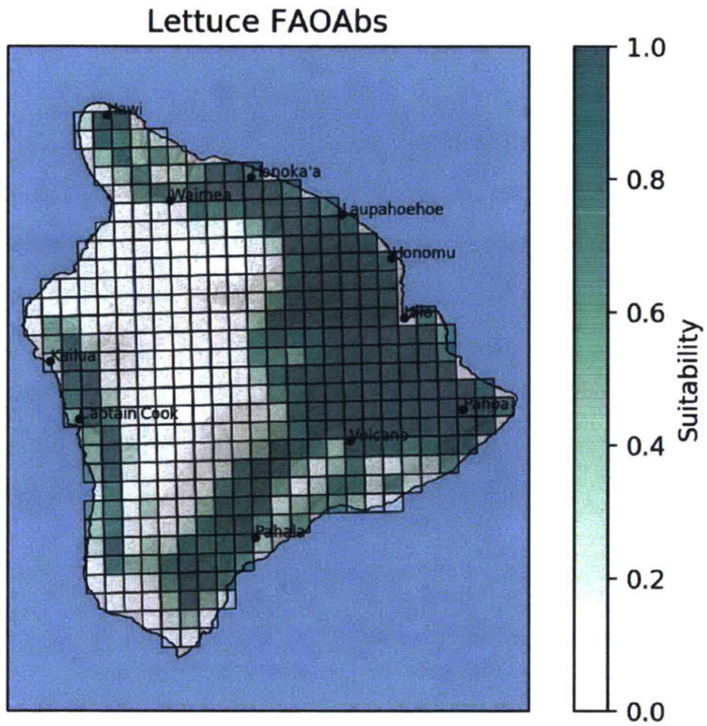

Figure A-10: Lettuce Suitability

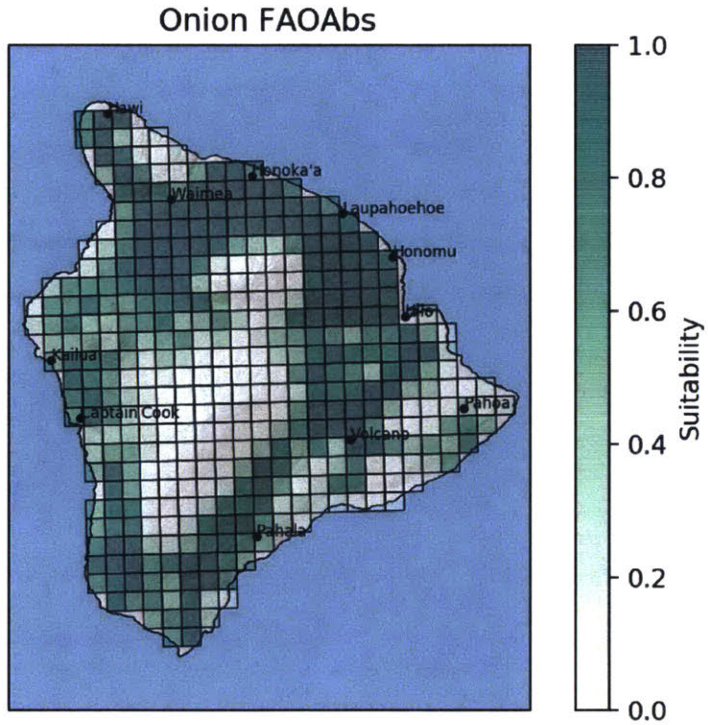

Figure A-11: Onion Suitability

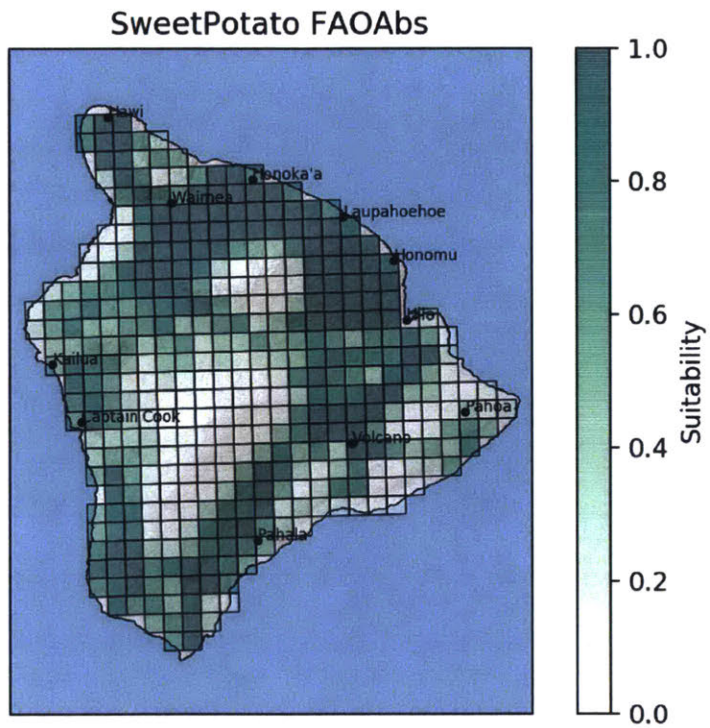

Figure A-12: Sweet Potato Suitability

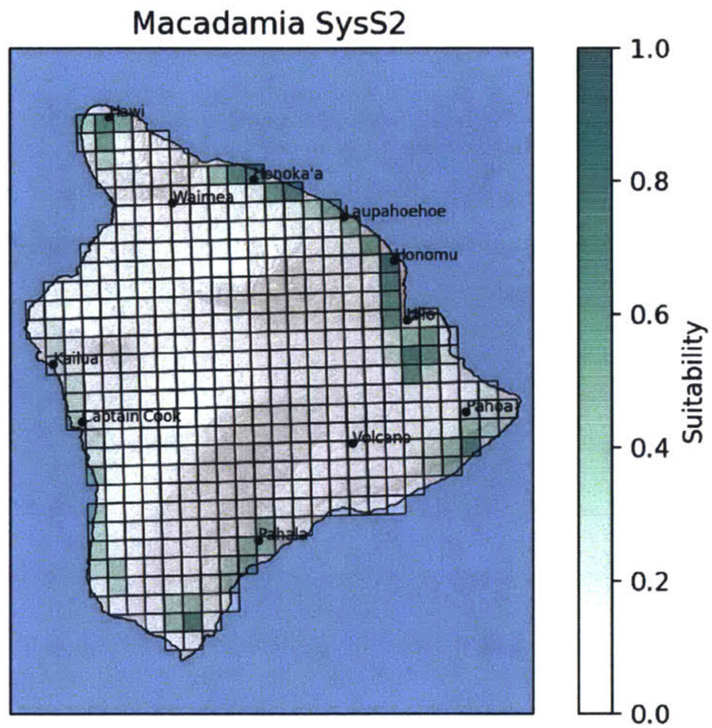

Figure A-13: Macadamia Suitability

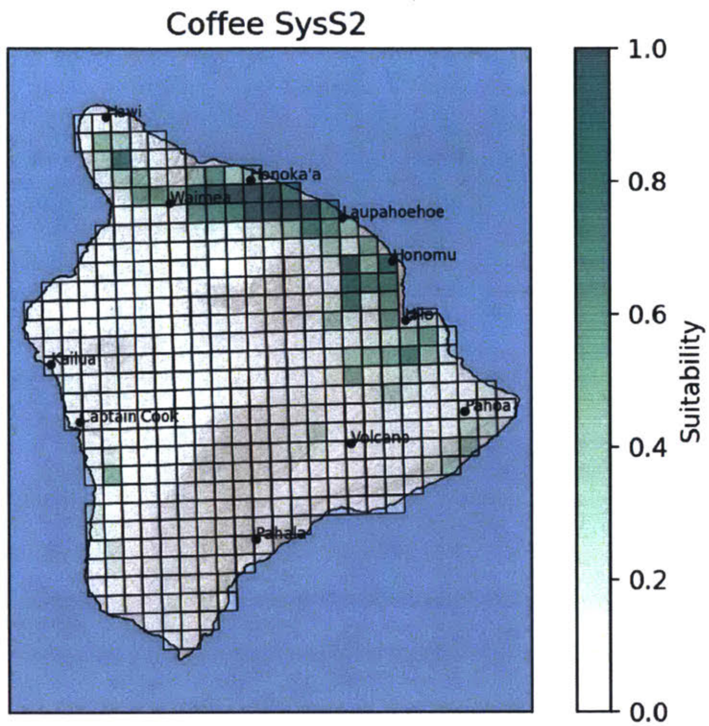

Figure A-14: Coffee Suitability

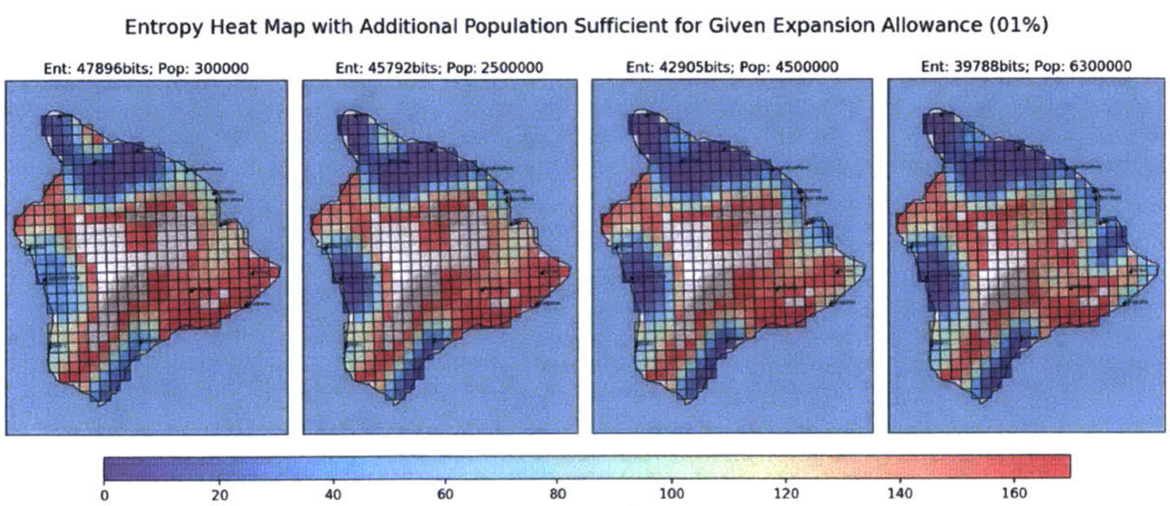

Figure A-15: Entropy Heat Map 01%

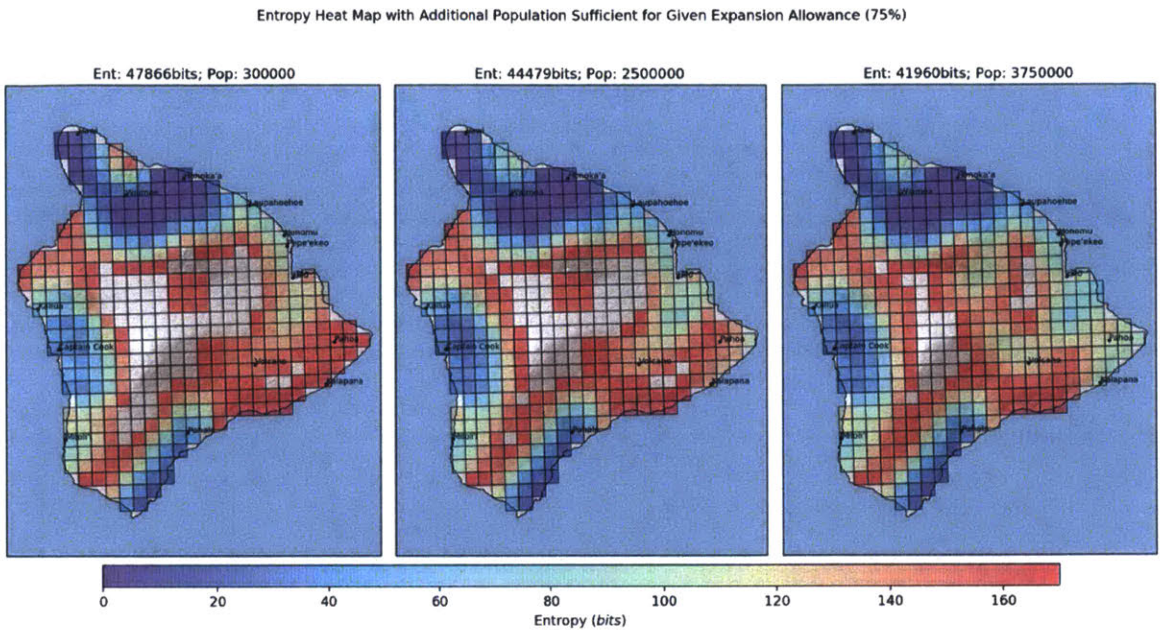

Figure A-16: Entropy Heat Map 75%

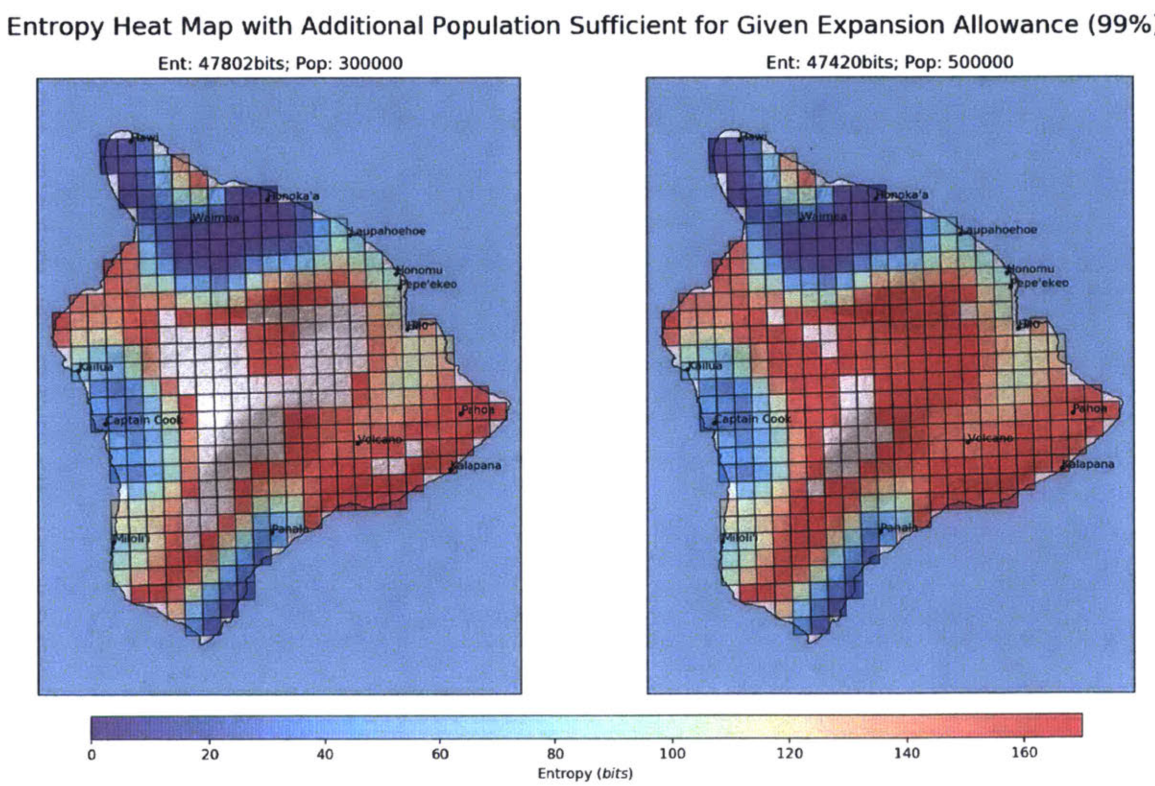

Figure A-17: Entropy Heat Map 99%

μ=0.50; ρ=5.3M	Cel	Cuc	Egg	Let	Oni	Swe	Tom	Bro	Ban	Avo	Mac	Cof	Com	Pas	Non
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.530	0.000	0.000	0.000	17.000	0.470
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	16.000	9.000
3	1.007	0.349	0.117	0.769	0.320	0.701	3.227	0.000	0.000	0.000	3.210	0.000	0.000	9.000	6.200
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.276	0.000	1.249	0.000	0.000	0.000	16.000	1.375
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.679	0.000	0.000	0.009	0.000	0.000	24.000	0.313
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.257	0.000	2.243	0.000	0.000	0.000	18.000	3.500
7	0.838	0.838	0.954	2.155	1.504	2.167	0.000	0.038	0.743	0.738	0.126	0.000	0.000	5.000	9.900
8	0.228	0.000	0.000	4.340	0.980	3.284	0.000	0.010	0.238	0.170	0.000	0.000	0.000	0.000	9.150
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.000	0.016	0.000	0.000	0.000	20.600	4.370
11	2.390	1.681	0.663	1.102	1.902	1.045	0.000	0.063	0.085	0.120	0.000	0.000	0.000	7.000	8.950
12	0.000	0.088	0.000	2.607	0.000	2.905	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	19.400
13	0.523	2.720	0.000	3.936	0.590	3.101	0.000	0.000	1.130	0.000	0.000	0.000	0.000	0.000	11.900
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.000	11.400
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	22.700	2.300
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.625	0.000	1.085	0.000	0.000	0.000	17.000	6.290
17	0.523	0.054	0.000	0.000	0.133	0.000	0.000	0.000	0.095	0.095	0.000	0.000	0.000	0.000	24.100
18	0.000	0.000	2.140	4.020	0.005	4.140	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	14.695
19	0.256	0.058	0.002	0.012	0.131	0.011	0.000	0.000	0.120	8.760	0.000	0.000	4.000	3.000	8.650
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.514	0.196	0.000	1.040	19.000	2.250
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.891	2.304	0.000	1.080	18.000	1.625
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.600	13.000	5.600
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	20.000	5.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.000	0.550	0.000	0.000	0.000	24.000	0.407
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.528	0.000	2.932	0.000	0.000	0.000	15.000	5.540
26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.000	20.000
27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	21.000	4.000
28	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.490	0.000	18.868	0.000	0.142	0.000	2.450	0.050
30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.535	0.000	0.000	6.400	12.000	2.065
31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.531	0.156	0.003	1.120	21.000	1.190
32	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.363	0.112	0.000	5.600	5.000	4.125
33	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000	23.000
34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.371	0.000	0.223	0.000	0.000	0.000	24.000	0.407
35	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.353	0.000	1.147	0.000	0.000	0.000	22.000	1.500
36	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.795	0.000	0.360	0.000	0.000	0.000	23.000	0.845
37	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
38	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
39	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.099	0.000	0.199	0.000	0.000	4.640	19.000	0.063
40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.537	0.000	0.098	0.000	0.000	4.800	15.000	1.565

Figure A-18: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

41	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.640	0.000	0.000	0.000	0.000	0.000	23.000	1.360
42	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.393	0.000	3.477	0.000	0.000	1.600	16.000	3.530
43	0.000	1.645	0.962	2.776	0.000	2.691	0.000	0.000	1.876	0.000	0.000	0.000	0.800	5.000	9.250
44	0.000	0.000	0.000	2.914	0.000	3.377	0.000	0.000	1.759	0.000	0.000	0.000	0.800	5.000	7.350
45	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	22.900
46	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
47	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
48	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.000	24.800	0.175
49	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
51	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
52	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.000	0.353	0.000	0.000	1.600	23.000	0.000
53	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.315	0.000	0.000	0.560	24.000	0.125
54	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.000	0.000	0.000	0.000	0.000	23.200	1.750
55	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.625	0.000	0.000	0.000	0.000	0.000	24.000	0.375
56	0.400	0.000	0.000	0.000	0.260	0.000	0.000	0.000	0.000	1.940	0.000	0.000	0.000	7.000	15.400
57	0.000	1.141	0.673	0.918	0.000	0.170	0.000	0.000	0.398	0.000	0.000	0.000	0.000	8.000	13.700
58	0.000	0.745	0.000	3.400	0.000	1.905	0.000	0.000	0.000	0.000	0.000	0.000	0.800	12.000	5.550
59	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	19.000
60	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
61	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.000	20.000
62	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
63	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	10.700	14.300
64	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.472	0.000	0.000	0.000	24.000	0.528
65	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
66	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000
67	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.000	0.000	16.800	8.170
68	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.500	21.500
69	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.000	0.000	0.000	8.600	16.300
70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.653	0.000	1.847	0.000	0.000	0.000	20.000	2.500
71	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.348	0.000	2.752	0.000	0.000	0.000	2.000	19.900
72	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
73	0.000	0.000	0.000	0.000	0.000	3.080	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8.000	13.920
74	0.000	0.938	0.372	3.039	0.000	0.551	0.000	0.000	0.000	0.000	0.000	0.000	0.160	15.000	4.940
75	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.000	22.000
76	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
77	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.400	23.600
78	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.017	0.000	0.000	0.000	16.300	8.680
79	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.122	0.000	2.278	0.000	0.000	0.000	1.000	21.600
80	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.258	0.000	0.053	0.000	0.000	0.000	22.000	1.690
81	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000	0.000	24.000	0.963

Figure A-19: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

82	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.088	0.000	0.000	0.000	11.800	13.100
83	0.000	0.000	0.000	0.000	0.000	0.000	1.160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	23.840
84	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
85	0.000	0.000	0.000	0.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24.928
86	1.430	0.353	0.059	0.861	0.542	1.518	1.688	1.450	0.000	4.100	0.000	0.000	0.000	1.000	12.000
87	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.690	0.000	2.510	0.000	0.000	0.000	0.000	21.800
88	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
89	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
90	0.000	0.000	0.000	0.000	0.000	1.140	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	22.860
91	0.000	0.000	0.000	4.283	0.000	3.779	0.000	0.000	1.690	0.000	0.098	0.000	0.000	5.000	9.450
92	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	21.700
93	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	24.000
94	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
95	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.200	21.800
96	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
97	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
98	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
99	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.200	23.800
100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.000	0.000	0.000	0.600	24.300
101	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
102	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
103	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
104	0.000	0.000	0.000	1.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	23.560
105	0.000	0.000	0.087	1.217	0.000	0.868	9.643	0.000	0.000	0.685	0.000	0.000	0.000	0.000	12.500
106	0.016	0.000	0.000	0.002	0.000	0.000	0.084	0.388	0.000	2.910	0.000	0.000	0.000	0.000	21.600
107	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
108	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
109	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
110	0.000	1.529	0.402	3.479	0.000	2.272	0.000	0.000	0.000	0.000	0.618	0.000	0.000	11.000	5.700
111	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	20.500
112	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
113	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.000	20.000
114	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.700	24.300
115	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	24.900
116	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
117	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
118	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
119	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
120	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
121	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
122	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000

Figure A-20: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

123	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
124	0.000	0.000	0.015	7.055	0.000	0.000	2.530	0.000	0.000	0.000	0.000	0.000	0.000	0.000	15.400
125	0.772	0.182	0.000	0.000	0.247	0.209	4.650	1.150	0.000	5.290	0.000	0.000	0.000	0.000	12.500
126	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.480	0.000	0.000	0.000	0.000	23.520
127	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
128	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
129	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
130	0.000	0.242	0.015	2.920	0.000	2.761	0.000	0.000	0.000	0.000	5.682	0.000	0.480	7.000	5.900
131	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24.200
132	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
133	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	9.000	16.000
134	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000	23.000
135	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.146	0.000	0.000	0.000	0.000	0.000	0.000	22.854
136	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
137	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
138	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
139	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
140	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
141	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
142	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.200	0.000	0.000	0.000	0.000	23.800
143	0.000	0.000	0.000	0.002	0.000	0.114	1.300	0.000	0.000	5.710	0.000	0.000	0.000	0.000	17.874
144	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.220	0.000	9.280	0.000	0.000	0.000	0.000	12.500
145	3.159	0.382	0.045	1.749	0.680	3.947	0.805	0.120	0.939	0.675	0.000	0.000	0.000	0.000	12.500
146	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
147	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
148	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
149	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
150	0.000	0.071	0.000	4.299	0.000	5.429	0.000	0.000	0.000	0.000	3.709	0.032	0.560	1.000	9.900
151	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	18.900
152	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000	19.000
153	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.000	14.000
154	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.129	0.000	0.000	0.000	0.000	0.000	4.000	18.871
155	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.891	0.000	0.000	0.000	3.000	19.109
156	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.994	0.000	0.040	0.000	0.000	0.000	0.000	22.966
157	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.058	0.000	0.000	0.000	0.000	0.000	0.000	22.942
158	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
159	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
161	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
162	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.170	0.000	0.928	0.000	0.000	0.000	0.000	23.902
163	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.900	0.000	0.000	0.000	4.000	16.100

Figure A-21: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

164	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.040	0.000	7.060	0.000	0.000	0.000	0.000	13.900
165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.543	0.000	0.000	0.000	0.000	24.457
166	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
167	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
168	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
169	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
170	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.000	22.000
171	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.000	22.000
172	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.712	0.000	0.000	0.000	21.288
173	0.000	0.446	0.041	4.448	0.000	1.880	0.000	0.000	0.178	0.000	1.156	0.000	0.000	0.000	6.750
174	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.000	16.000
175	0.744	0.000	0.135	0.832	0.401	0.802	1.440	1.500	0.000	0.000	0.167	4.228	0.000	9.000	5.750
176	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.000	24.600	0.383
177	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.955	0.000	1.230	0.000	0.000	0.000	19.000	2.815
178	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.451	0.000	0.340	0.000	0.000	0.000	0.000	24.209
179	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.038	0.000	0.000	0.000	0.000	0.000	0.000	22.962
180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.453	0.000	0.000	0.000	0.000	0.000	0.000	20.547
181	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
182	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
183	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
184	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
185	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
186	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
187	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
188	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
189	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
190	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
191	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
192	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8.000	17.000
193	0.000	1.122	0.555	7.465	0.000	0.254	0.000	0.000	0.000	0.000	1.804	0.000	0.000	3.000	10.800
194	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.548	0.000	0.000	2.000	17.452
195	0.000	0.010	0.000	0.171	0.000	4.327	0.000	0.000	3.380	0.000	1.313	0.000	0.000	3.000	7.700
196	0.000	2.119	0.000	0.000	0.000	0.000	0.000	3.830	0.000	0.000	1.293	2.133	0.000	5.000	10.625
197	0.000	8.239	0.000	0.000	0.000	0.000	0.000	2.380	0.000	0.000	0.000	0.000	0.000	4.000	10.381
198	0.000	0.000	0.000	0.000	0.000	0.000	0.000	10.700	0.000	0.000	0.000	0.000	0.000	4.000	10.300
199	1.790	1.790	0.000	0.000	1.790	1.790	1.800	1.570	0.000	0.000	0.000	0.000	0.000	0.000	14.470
200	0.000	0.559	0.000	0.000	0.000	0.000	0.000	0.875	0.000	0.000	0.000	0.000	0.000	0.000	23.566
201	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.562	0.000	0.000	0.000	0.000	0.000	0.000	23.438
202	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
203	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
204	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000

Figure A-22: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

205	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
206	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
207	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
208	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.940	0.000	1.960	0.000	0.000	0.000	0.000	20.100
209	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
210	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
211	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
212	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
213	0.000	0.000	0.000	0.000	0.000	10.303	0.000	0.000	0.000	0.000	0.297	0.000	0.000	4.000	10.400
214	0.000	1.634	0.218	4.870	0.000	1.210	0.000	0.000	0.000	0.000	2.218	0.000	0.000	7.000	7.850
215	0.000	2.778	2.076	3.688	0.000	3.880	0.000	0.000	0.128	0.000	0.000	0.000	0.000	0.000	12.450
216	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
217	0.566	0.000	0.000	0.297	0.396	0.591	0.820	2.760	0.000	0.000	1.124	2.097	0.000	11.000	5.350
218	0.000	0.000	0.266	0.464	0.000	0.000	0.000	0.373	0.000	0.000	0.050	0.846	0.000	22.000	1.000
219	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.095	0.000	0.000	0.000	0.000	0.000	23.000	0.905
220	0.000	1.105	0.000	0.000	0.000	0.000	0.000	4.080	0.000	0.000	0.000	0.000	0.000	15.000	4.815
221	0.000	0.559	0.000	0.000	0.000	0.000	0.000	2.200	0.000	0.000	0.000	0.000	0.000	0.000	22.241
222	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
223	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
224	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
225	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
226	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
227	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
228	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
229	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.188	0.000	1.270	0.000	0.000	0.000	0.000	23.542
230	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.280	0.000	0.000	0.000	0.000	21.720
231	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
232	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
233	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.000	24.991
234	0.000	0.000	0.000	0.000	0.000	6.550	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.000	6.450
235	0.000	3.020	0.000	0.030	0.000	7.402	0.000	0.000	0.000	0.000	0.000	0.098	0.000	4.000	10.450
236	0.000	1.083	0.000	4.978	0.000	6.439	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.500
237	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
238	0.000	0.000	0.000	12.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.500
239	0.685	0.000	0.000	4.836	0.685	3.440	0.000	0.000	1.704	0.000	0.000	0.000	0.000	0.000	10.950
240	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000	19.500
241	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.556	0.000	0.000	0.943	1.970	0.000	17.000	2.530
242	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.544	0.000	0.000	0.000	0.016	0.000	18.000	3.440
243	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.655	0.000	0.000	0.000	0.000	0.000	22.000	1.345
244	1.370	0.000	0.000	0.000	0.950	2.300	4.010	1.370	0.000	0.000	0.000	0.000	0.000	5.000	10.000
245	0.000	0.000	0.000	0.000	0.000	0.000	1.750	0.000	0.000	0.000	0.000	0.000	0.000	0.000	23.250

Figure A-23: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

246	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
247	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
248	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
249	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
251	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
252	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.470	0.000	5.990	0.000	0.000	0.000	0.000	14.540
253	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.110	0.000	0.000	0.000	0.000	19.890
254	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
255	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
256	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000	19.000
257	0.000	0.000	0.000	0.000	0.000	1.260	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	22.740
258	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
259	0.000	0.001	0.000	11.409	0.000	1.090	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.500
260	0.000	1.606	0.000	9.054	0.000	1.840	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.500
261	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	24.000
262	0.255	3.622	1.684	0.000	0.255	3.377	0.000	0.000	3.306	0.000	0.000	0.000	0.000	0.000	12.500
263	5.276	0.000	0.000	1.468	0.744	4.954	0.000	0.000	0.000	0.108	0.000	0.000	0.000	0.000	12.450
264	0.509	0.319	0.000	0.000	0.065	0.606	1.857	3.480	0.000	0.000	1.997	3.417	0.000	6.000	6.750
265	1.668	1.192	0.930	3.189	1.516	1.658	1.286	1.060	0.000	0.000	0.000	0.000	0.000	0.000	12.500
266	1.253	0.596	0.382	1.060	1.029	1.271	1.148	5.360	0.000	0.000	0.000	0.000	0.000	1.000	11.900
267	2.329	0.519	0.000	0.000	0.349	1.479	4.134	3.190	0.000	0.000	0.000	0.000	0.000	1.000	12.000
268	0.000	0.000	0.000	0.000	0.000	0.000	0.373	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24.627
269	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
270	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
271	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
272	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
273	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
274	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
275	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.400	23.600
276	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.900	0.000	10.800	0.000	0.000	0.000	0.000	12.300
277	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.820	0.000	0.000	0.000	8.000	15.180
278	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	24.000
279	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.000	21.000
280	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
281	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
282	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
283	0.000	0.699	0.375	0.524	0.000	7.937	0.000	0.000	0.365	0.000	0.000	0.000	0.000	1.000	14.100
284	1.030	2.091	0.997	0.000	1.030	3.142	0.000	0.000	4.210	0.000	0.000	0.000	0.000	0.000	12.500
285	5.352	0.000	0.000	3.798	3.701	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.150
286	0.498	0.180	0.073	0.455	0.232	0.546	1.106	3.090	0.000	1.030	1.099	0.891	0.000	8.000	7.100

Figure A-24: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

287	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.223	0.000	3.830	0.000	0.007	0.000	15.000	4.940
288	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.090	0.000	0.000	0.000	23.100	1.810
289	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.700	0.000	0.000	0.000	0.000	0.000	15.000	7.300
290	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24.970
291	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
292	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
293	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
294	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
295	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
296	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
297	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.200	24.800
298	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
299	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	24.500
300	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
301	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
302	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
303	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
304	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
305	1.550	1.299	0.271	0.000	1.550	4.939	0.000	0.000	2.391	0.000	0.000	0.000	0.000	1.000	12.000
306	5.204	0.000	0.000	5.412	0.886	0.299	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.700
307	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.400	0.000	2.010	0.668	0.077	0.000	11.000	2.345
308	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.096	0.000	0.000	17.000	7.890
309	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.055	0.000	0.385	0.000	0.000	0.000	16.000	8.560
310	0.098	0.098	1.010	0.000	0.098	2.060	6.210	0.098	0.000	0.000	0.000	0.000	0.000	3.000	12.330
311	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
312	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
313	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
314	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
315	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
316	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
317	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
318	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.000	0.000	0.000	0.100	24.800
319	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
320	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
321	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
322	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
323	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
324	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
325	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
326	2.189	0.000	0.000	7.722	0.000	0.823	0.000	0.000	0.000	0.000	0.266	0.000	0.000	1.000	10.400
327	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8.000	17.000

Figure A-25: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

328	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.035	0.000	0.015	0.000	0.000	0.000	11.000	6.950
329	0.000	0.000	0.032	2.040	0.000	1.440	8.988	0.000	0.000	0.000	0.000	0.000	0.000	0.000	12.500
330	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
331	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
332	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
333	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
334	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
335	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.100	23.900
336	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.100	17.900
337	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
338	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
339	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
340	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
341	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
342	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
343	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	21.500
344	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	16.800
345	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	24.000
346	0.000	0.000	0.000	0.000	0.000	0.000	0.000	9.700	0.000	0.000	0.000	0.000	0.000	6.000	9.300
347	0.000	0.000	0.000	0.000	0.000	1.900	6.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	17.027
348	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
349	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
350	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
351	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.493	0.000	0.000	0.000	0.000	24.507
352	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.316	0.056	0.028	0.000	1.000	19.600
353	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	1.454	0.151	0.324	1.200	17.000	4.870
354	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.680	0.000	0.865	0.000	0.000	0.000	3.000	19.455
355	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
356	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.400	0.000	0.000	0.000	0.000	0.000	0.000	24.000
357	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.615	0.000	0.478	0.000	0.000	0.000	0.000	16.807
358	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	21.000
359	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	20.100
360	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.900
361	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	18.900
362	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000	19.000
363	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.900	20.100
364	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
365	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
366	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
367	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
368	0.388	0.020	0.000	0.567	0.051	0.472	0.000	0.000	0.067	0.235	0.000	0.000	0.000	0.000	23.200

Figure A-26: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

369	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.238	0.000	7.110	0.359	0.472	3.120	5.000	7.700
370	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.133	0.000	2.900	7.462	0.555	0.000	9.000	3.950
371	1.076	0.342	0.115	1.323	0.461	1.194	2.620	0.965	0.000	0.005	0.000	0.000	0.000	0.000	16.900
372	0.000	0.000	0.000	0.000	0.000	0.000	0.177	0.423	0.000	0.000	0.000	0.000	0.000	0.000	23.600
373	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000	17.900
374	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.232	3.057	0.211	0.000	6.500	15.000
375	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.200	19.800
376	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.000	0.000	0.000	0.000	24.700
377	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
378	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
379	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
380	0.384	0.245	0.118	0.390	0.289	0.388	1.078	4.500	0.250	0.158	0.075	0.045	2.880	7.000	7.200
381	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.090	7.160	1.155	2.000	5.000	4.595
382	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.966	4.133	0.050	0.000	17.000	1.850
383	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.394	0.000	3.880	1.526	0.000	0.000	13.000	5.200
384	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.180	0.000	2.454	12.365	0.000	0.000	0.000	10.000
385	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
386	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
387	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.000	0.105	0.000	0.000	0.000	0.000	24.800
388	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
389	0.062	0.000	0.000	0.116	0.000	0.088	0.000	0.000	0.133	0.000	0.000	0.000	0.000	1.000	23.600
390	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	23.500	1.490
391	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.198	0.000	0.000	0.002	0.000	0.000	10.000	5.200
392	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24.300
393	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
394	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
395	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
396	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
397	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.078	0.000	0.313	0.809	0.000	0.000	0.000	21.800
398	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.685	0.305	0.000	0.000	16.000	7.010
399	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.378	0.000	1.776	0.181	0.000	0.000	17.000	2.065
400	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
401	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
402	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
403	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.994	0.000	2.390	0.000	0.000	0.000	3.000	12.616
404	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.064	0.000	0.645	0.691	0.000	0.000	9.000	7.600
405	0.360	0.221	0.134	0.386	0.254	0.373	0.573	0.068	0.000	3.230	0.032	0.021	0.000	14.000	5.350
406	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	1.207	0.011	0.000	0.000	11.000	1.150
407	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000
408	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.000	18.000
409	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.000	0.000

Figure A-27: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

410	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.080	0.000	0.000	0.000	18.900	3.390
411	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	10.000	10.400
412	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	22.000	2.500

Figure A-28: (con't) Spreadsheet of Cropland and Non-Crop Land Areas for $\mu = 0.50$ and $\rho = 5300000$. Areas are expressed in km^2. For more data on different scenarios, contact jonkaneshiro@alum.mit.edu

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