Potential for Ethanol Production in Hawaii

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by

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Executive Summary

An assessment of biomass-based ethanol production potential was conducted for the State of Hawaii considering lands, crops, and conversion technologies. Evaluation of the spatial distribution of soil types, zoning, and annual rainfall, were conducted using geographic information system technology. The Natural Resources Conservation Service designation for soil types suitable for specific crops – sugar and wood species – was used as a first identifier of land suitability. These lands were further reduced by restricting consideration to the subset zoned for agricultural use. Within the agriculturally zoned land in the state suitable for sugar and wood production, lands owned by the State of Hawaii, those owned by large land owners, and agricultural lands of importance to the state of Hawaii, were considered as sub-groups. Acreage for each is summarized in the Table ES1. Values range from 50,000 acres for NRCS sugar soils that are zoned for agriculture and owned by the State of Hawaii to nearly 700,000 acres for NRCS woodland soils that are zoned agricultural. Note that NRCS designations of soils suitable for sugar and wood are not mutually exclusive, i.e. some areas are suitable for either crop, and this is reflected in the acreages in the table.

Sugar cane, banagrass, *Leucaena,* and *Eucalyptus* were selected as potential ethanol feedstock crops based on historical crop production in Hawaii or extensive energy crop research trials and demonstrations conducted over the past 30 years. Sugar cane provides fermentable sugars and fiber, whereas the latter three crops are grown for fiber only. Crop water requirements were compared with annual rainfall for the selected land areas. It was assumed that sugar and banagrass would require at least 78 inches of irrigation annually, via rainfall or mechanical application; thus, lands receiving less than 78 inches of rainfall would need some applied irrigation to supplement rainfall. It was assumed that the wood crops, *Leucaena* and *Eucalyptus,* would be grown without applied irrigation, that *Leucaena* was suitable for drier locations (20 to 40 inches), and that *Eucalyptus* was suitable for the areas receiving more than 40 inches of annual rainfall.

Historic production data for unirrigated (rainfed) and irrigated sugar cane in Hawaii were used to calculate average raw sugar yields of 4.2 and 6.4 tons per acre per year, respectively. Based on these values and molasses and fiber data, associated total fermentable sugar and fiber yields were calculated to be 4.6 and 7.1 tons per acre per year for unirrigated sugar cane and 7.0 and 10.9 tons per acre per year for irrigated sugar cane. Unirrigated banagrass and irrigated banagrass fiber yields were assumed to be 18 and 22 tons per acre per year, respectively. Fiber yields from *Leucaena* and *Eucalyptus* were estimated to be 10 tons per acre per year based on field trials and demonstration plantings.

Yields from sugar and fiber were assumed to be 141 gallons of ethanol per ton of fermentable sugars and 70 gallons of ethanol per ton of fiber. These were used to calculate total potential statewide ethanol production as shown in Table ES1. Four crop scenarios are presented; 1) sugar cane grown on all soils suitable for sugar, 2) *Leucaena* and *Eucalyptus* grown on all soils suitable for trees, 3) sugar cane given first priority, grown on all soils suitable for sugar, and *Leucaena* and *Eucalyptus* given second priority, grown on remaining soils suitable for wood, and 4) banagrass grown on all soils suitable for sugar. The third crop scenario produced the most ethanol for each of the land subgroups with a maximum value slightly greater than 700 million

gal ethanol per year. For comparison, the total motor gasoline sales in Hawaii in 2005 totaled 454 million gallons or 668 million gallons of ethanol on an energy equivalent basis. A renewable fuels target of 20% of motor gasoline, 134 million gallons of ethanol equivalent, could be produced under all crop scenarios with the exception of state owned lands under scenarios 1, 2, and 4.

Table ES1. Summary of statewide ethanol potential for four land groupings and four crop scenarios.

	Zoned Ag	Zoned Ag, State Owned	Zoned Ag, Large Land Owners	Zoned Ag, ALISH[1]
1) Sugar cane				
Acres	360,324	50,828	252,145	329,520
Ethanol (mil gal/yr)	429	61	312	393
2) Trees				
Acres	698,632	160,360	491,040	571,060
Ethanol (mil gal/yr)	489	112	344	400
3) Sugar first priority, trees second priority				
Sugar Acres	360,324	50,828	252,145	329,520
Wood Acres	394,136	115,488	288,105	294,564
Ethanol (mil gal/yr)	705	142	513	599
4) Banagrass				
Acres	360,324	50,828	252,145	329,520
Ethanol (mil gal/yr)	525	74	374	480

[1] ALISH = Agricultural Lands of Importance to the State of Hawaii

The crop scenarios of the summary table do not reflect near-term potential ethanol production. For the purposes of this study, 2010 production of ethanol from molasses from existing sugar factories using readily available conversion technology was considered near term. Production costs for ethanol from molasses were estimated to be $1.45 to $1.58. Comparison of estimated ethanol import costs based on west coast spot market prices and shipping costs ranged from $2.00 to $4.54 per gallon landed in Hawaii suggesting that ethanol production from local feedstock could be cost competitive. Similarly, $1.50 per gallon ethanol from molasses would equal $2.25 per gallon of gasoline on an energy equivalent basis. Average retail gasoline prices without taxes were $2.35 per gallon on December 1, 2006, suggesting that ethanol could be cost competitive with gasoline under favorable market conditions.

The scope of this report was to explore the potential for producing ethanol in Hawaii from indigenous feedstocks. This has been accomplished at a level that does not address many of the implementation issues that will be critical to such an endeavor: water availability and cost, land availability, land use priorities, impacts on environmental quality, economic impacts, and costs of production for ethanol conversion technologies that are currently in the development stage. Each of these merits additional study whether for guiding future government policy making or investing in ethanol production ventures.

Table of Contents

List of Figures

List of Tables

Nomenclature

ALISH	Agricultural Lands of Importance to the State of Hawaii; land identified under agricultural productivity rating system adopted by the Board of Agriculture on January 28, 1977
C	capital cost of distillery to make fuel grade ethanol from molasses
CARBOB	California Reformulated Blendstock for Oxygenate Blending as designated by the State of California Air Resources Board
LLO	Large Land Owners as defined by the State of Hawaii; includes public and private ownership of at least 1000 acres on a given island
NRCS	Natural Resources Conservation Service, a unit of the United States Department of Agriculture
Q	production volume of distillery to make fuel grade ethanol from molasses
SOH	State of Hawaii
SS	sugar soils; soils suitable for sugar production as designated by the Natural Resources Conservation Service
USDA	United States Department of Agriculture
WS	woodland soils; soils suitable for woodland as designated by the Natural Resources Conservation Service
ZA	zoned agricultural

1. Introduction

Hawaii is the most isolated island archipelago in the world. Our nearest continental neighbor is North America, nearly 2400 miles away [1]. This isolation gives rise to certain challenges with respect to energy supply and security. Hawaii relied on fossil fuels for nearly 94% of its energy needs as of 2004 [2]. Having no fossil fuel resources of its own, Hawaii must import all of its fossil fuel from abroad. This heavy reliance on imported energy puts the state in a vulnerable position with respect to energy security.

In recognition of this problem, State lawmakers have issued mandates and enacted laws to address some of the problems inherent in our energy supply system. Important initiatives call for 20 percent of our electricity demand to be supplied by renewable resources and 20 percent of our transportation fuel demand to be supplied by alternative fuels by the year 2020. The recently implemented ethanol mandate, requiring that 85% of gasoline sold in Hawaii contain 10% ethanol by volume, is a key milestone in achieving the 2020 goals.

Presently none of the ethanol used to meet the 10% standard is produced in the State of Hawaii, although at least four groups are in the process of developing production facilities located within the State [3]. Until ethanol is produced locally, the State's reliance on imported energy to meet the ethanol mandate will not be reduced. To facilitate the development of local ethanol production facilities the State has funded a wide variety of research on available resources, feasibility, and economics of producing ethanol in Hawaii, of which this report is the most recent.

Leading up to the implementation of the 10% ethanol mandate, studies on the economic impact and feasibility of producing ethanol in Hawaii were conducted by Stillwater and Associates and BBI International. The reports, *Hawaii Ethanol Alternatives* [4] and *Economic Impact Assessment for Ethanol Production and Use in Hawaii* [5] were submitted in draft form in 2003.

This report attempts to update some of the information included in those reports and provide ethanol production potential on a county by county basis for near-, mid-, and long-term time frames. In our analysis, near term is considered to be 2010 or earlier, mid-term to 2015 and long term to 2025.

Variables affecting ethanol production potential in Hawaii include land availability, land suitability, conversion technologies, economic incentives, public policy, public sentiment, water availability, petroleum pricing, demand growth, and labor availability.

Three main areas must be addressed to estimate ethanol production potential in the State of Hawaii. First, land availability and suitability must be assessed to establish potential limits to feedstock cost and availability. Second, based on the results of the land survey and taking time frame into consideration, feedstock and conversion technology can be selected. Finally, the cost of production must be evaluated by estimating feedstock and conversion costs.

As a precursor to developing this report, a review of Hawaii bioenergy literature was conducted. This included reports of energy crop development field trials, economic impact studies, and reports on methanol and fuel ethanol production potential. Special consideration was given to studies conducted within the last decade on ethanol production potential for the State [4, 5, 6, 7, 8].

Review of the above reports and supporting material going back to the 1970's provided valuable insight into the progression of sustainable energy research and development in Hawaii related to biomass. The body of work conducted over the last thirty plus years is far too great to cover completely here but a brief synopsis of some of the more pertinent material is provided below.

2. History and Literature Review

Hawaii's vulnerability to energy supply disruption was felt during the energy crisis of the 1970's and served to demonstrate the difficulties that a major interruption to energy supply could cause. This new awareness of our domestic dependence on foreign energy supplies resulted in a flurry of research and development activity in alternative energy technologies.

At the state level, the legislature enacted a variety of energy related bills during the 1974 session including the creation of the Hawaii Natural Energy Institute (HNEI), the Natural Energy Laboratory of Hawaii (NELH, now NELHA), the State Program for Planning and Conservation, and the position of State Energy Resources Coordinator. As these new agencies and groups got their feet under them the alternative energy research being conducted in the State increased dramatically.

The areas of solid waste, biomass, hydroelectric, wind, geothermal, solar, ocean thermal energy conversion (OTEC), and wave/tidal energy were identified as potential sources of alternative energy in Hawaii. Hawaii's unique environment, year round growing season, ocean access, geothermal potential, and areas of high wind, made it a natural choice for siting alternative energy research. Large projects for wind at Kahuku on Oahu and South Point on the Hawaii, OTEC at Keahole, solid waste conversion on Oahu, geothermal in Puna, and biomass at various sugar plantations statewide evolved over the ensuing years. Some of these projects remain in place today, although not all are being operated as originally envisioned.

Of the available alternative energy sources originally identified, only biomass was a potential source of transportation fuel. For this reason a concerted effort was made to develop technology and resources in this area. Early work built on Hawaii's agricultural history and extensive experience with sugar cane and pineapple production. Investigations and experimental trials were conducted to identify favorable plant species for dedicated energy crop production. Long-term field trials were initiated to study a variety of areas including cultivation, harvesting methods and yield characteristics [9, 10, 11, 12, 13, 14, 15, 16].

Concurrently with the biomass feedstock production studies, work on converting biomass to liquid fuel was also conducted. The rapid improvements in computing power beginning in the 1980's enabled work on crop suitability modeling to develop. A great deal of effort was spent developing a database with various important agronomic values, such as, rainfall, insolation, wind conditions, slope, soil series, for the entire State. The Hawaii Natural Resource

Information System (HNRIS), as the database was called, was used to match crops to suitable lands or vice versa [17].

In the late 1980's and early 1990's the Hawaii Integrated Biofuels Research Program (HIBRP) explored the feasibility of growing dedicated energy crops for conversion into liquid transportation fuels, primarily methanol and ethanol. The research areas included species selection and yield characteristics, harvesting and yield model development, and conversion technology development [18].

A 1993 report by Hubbard and Kinoshita, *Investigation of Biomass-for-Energy Production on Molokai*, explores the feasibility and operation of dedicated biomass energy crop production on the Island of Molokai. The report contains detailed coverage of water issues including consideration of availability, access, infrastructure and cost. Plantation operation and management schemes are also covered in depth. Estimated delivered costs are listed as $56.44 for banagrass and $82.13 for tree crops on a delivered dry ton basis [19].

In 1994 a mandate requiring blending of ten percent ethanol in motor fuel was introduced through Act 199. The language included in Act 199 later became part of Chapter 486E of the Hawaii Revised Statutes. The lack of a local supply of ethanol and a system for enforcement, along with resistance from the petroleum supply chain stalled the implementation of the mandate until the spring of 2006. The most recent version of the mandate is set forth in Title 15, Chapter 35 of the Hawaii Administrative Rules [20].

The absence of local supplies of ethanol was recognized as a hurdle to implementing the ethanol mandate and several studies on local ethanol production potential were commissioned [6, 7, 21]. These reports addressed technological, economic, and environmental constraints to local ethanol production.

In a 1994 report, *Ethanol Production in Hawaii*, Dr. Robert Shleser investigated ethanol production potential from readily available feedstocks, including bagasse, molasses, cane trash, newspaper, and municipal solid waste, as well as experimental crops, *Leucaena*, *Eucalyptus*, sweet sorghum, and napier grass. The report describes seven integrated biomass to ethanol conversion technologies and briefly touches on the traditional fermentation of sugars to ethanol. Economics and marketing are also covered with consideration given to co-products and alternate uses such as electricity generation. The report estimates ethanol production costs in the range of $0.94 to $3.65 depending on feedstock and conversion technology [6].

Another study conducted concurrently with Dr. Shleser's work was the *Sustainable Biomass Energy Program: Hamakua Project*. This study was developed to address potential uses for abandoned sugar lands following the shuttering of the sugar industry on Hawaii. Administered by the Pacific International Center for High Technology Research (PICHTR), the Hamakua Project included input from over thirteen entities encompassing local and national corporations, state and federal research organizations and university researchers [21].

The study investigated crop suitability, land availability, ethanol conversion options and economics, electricity conversion options and economics, and other considerations including permitting and co-product markets. Ethanol production costs were estimated to range from $0.52 to $2.92 depending on feedstock costs and conversion technology. The study also reported that feedstock costs needed to be kept below $50 per dry ton to be competitive for energy production in Hawaii [21].

In the 1999 report, *Siting Evaluation for Biomass-Ethanol Production in Hawaii* [7], Kinoshita and Zhou evaluate seven candidate sites spanning the four larger islands for ethanol-feedstock production. Of the seven sites, three are chosen for a more in depth analysis; Hawaiian Commercial and Sugar Company (HC&S) on Maui, former Waialua Sugar Company lands on Oahu, and former Hamakua Sugar Company lands on the island of Hawaii.

The report includes information on crop selection, land suitability and availability, supplemental feedstocks including municipal solid waste (MSW) and bagasse, feedstock production costs for the candidate crops, and case studies for the three sites mentioned above. Reported delivered feedstock costs range from $54 per dry ton for eucalyptus to $85 per dry ton for sugar cane and *Leucaena*. Banagrass delivered cost was estimated to be $66 per dry ton. The above estimates excluded land holding costs [7].

Rising crude oil prices and continuing tension in the Middle East propelled energy issues to the forefront in 2002-2003. As a result, several reports covering production alternatives, economic impacts and biomass resources were completed.

The 2002, *Biomass and Bioenergy Resource Assessment, State of Hawaii* [22], details the biomass resources available in four major categories, animal wastes, forestry residues, agricultural waste, and urban waste. The largest sources of biomass are MSW and agricultural waste generated by the sugar companies. A detailed breakdown of each category can be found in the report.

Hawaii Ethanol Alternatives, a study by Stillwater and Associates [4] was conducted in 2003. This study covered supply potential, ethanol markets, production and delivery logistics, impacts on local refiners, and a cost benefit analysis. Ethanol production costs, including 24% profit margin but excluding subsidies, are estimated to be between $1.52 and $1.86 per gallon using sugar and molasses from sugar cane as feedstock. The authors concluded that ethanol could be produced in Hawaii at low enough prices to be competitive in export markets on the continental United States.

A second study by BBI International, titled *Economic Impact Assessment for Ethanol Production and Use in Hawaii* [5], was also conducted in 2003. This report sought to address the economic impacts of implementing the ethanol mandate. Included in the report is an inventory and analysis of the available indigenous feedstocks. The authors concluded that sugar cane, MSW, food waste, and pineapple residues were available in quantities sufficient to justify consideration for conversion to ethanol. The remainder of the report details the economic impacts expected from a variety of ethanol production facility development scenarios.

3. Methodology

With regard to ethanol potential for the State of Hawaii, this report was to provide, "Estimates of production potential—short-term (to 2010), mid-term (to 2015), and long-term (to 2025)—by county, with consideration of available, and probable feedstocks and ethanol production technologies; and estimates of costs of production and cost effectiveness in the short term."

The investigation was organized as follows:

- Review the literature to identify pertinent data and potential sources for input on ethanol conversion and crop production.
- Review conversion technologies, commercial and under development.
- Review and inventory available and potential sources of feedstock for ethanol conversion.
- Inventory agricultural lands and determine their suitability for energy crop production.
- Model/estimate yields for various crops based on available lands.
- Estimate ethanol conversion for identified feedstocks, based on conversion technology for the short-, mid-, and long-term cases.
- Estimate cost of production for near-term case.

4. Conversion Technologies

4.1 Fermentation

Ethanol has historically been produced through fermentation of sugars, most commonly as an ingredient in beer, wine, and other spirits. At industrial scales, sugars are derived directly from sugar bearing plants (e.g. sugar cane) or indirectly from plant starches (e.g. corn). In the United States, commercial production of ethanol primarily occurs via fermenting of corn milled using both wet and dry methods. Outside of the United States, ethanol is primarily produced using sugar cane or sugar beets as a sugar source. In Hawaii, sugar cane is seen as the crop of choice for sugar based production of ethanol.

Production of ethanol from sugar cane or other sugar bearing plants involves extracting the sugars and fermenting them directly. Sugar cane processing facilities can be designed to split the extracted juices between sugar and ethanol production. Molasses contains sugars that are economically unrecoverable in the manufacture of raw sugar and is sold as a byproduct by Hawaii's producers, some of it locally as a cattle feed supplement. The sugars present in molasses can be fermented to produce ethanol and this is the basis for rum production. A yield of

141 gallons of ethanol per ton of fermentable sugars can be expected from these sources and this translates to 70 gallons per ton of molasses.

Fermentation is the only commercially viable non-petroleum based process for producing ethanol. Other methods have shown promise and are described below but none are currently being applied at the commercial scale.

4.2 Fiber Hydrolysis Followed by Fermentation

The cellulose and hemicellulose components of plant fiber can also be processed to provide a source of sugar for fermentation. Ethanol from biomass fiber via fermentation pathways has seen continued development. Fiber is composed of cellulose, hemicellulose, and lignin. The first two components are polysaccharides that can be broken down or hydrolyzed into simple sugars such as glucose that can subsequently be fermented into ethanol. Hydrolysis can be accomplished using dilute acid solutions, enzymes, or a staged combination of the two. Pretreatment of fiber to make the chemical linkages between the substituent sugars more amenable to hydrolysis is the focus of ongoing research. Ethanol from fiber is widely viewed as the process that will ultimately provide plentiful supplies of fuel but has yet to be realized at a commercial scale.

Economics and development challenges are addressed in a technical report produced by The National Renewable Energy Laboratory (NREL) titled *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover* [23].

4.3 Thermochemical

A third pathway to ethanol is via thermochemical conversion. This involves partially oxidizing biomass to produce a synthesis gas (CO and H_2), which can be converted to ethanol using a modified Fischer Tropsch process. The integrated process is currently approaching the demonstration scale.

The production of ethanol from fiber via thermochemical conversion is currently receiving attention in Hawaii. Clearfuels Technology, a local company, has licensed technology for the Pearson process, a syngas to ethanol route via Fischer Tropsch synthesis. The process has been tested at a scale of 5 tons biomass per day at Pearson's pilot plant in Aberdeen, Mississippi and a 50 ton biomass per day demonstration unit is currently under development at the same location. Tests conducted at this facility will provide data necessary to determine cost of production ($/gal ethanol) and product yield (gal ethanol per ton of biomass) [24].

5. Feedstocks

5.1 Available Feedstocks

Hawaii has a number of existing municipal and agricultural waste streams that might be suitable for ethanol conversion. This resource base has been well characterized by a number of studies [4, 5, 6, 22]. The biogenic fractions of waste streams (e.g. municipal solid waste, food waste, sewage sludge, and animal waste) can be excellent candidates for energy conversion because they often have low or negative cost. However, small, dispersed volumes, separation issues, and lack of collection infrastructure, often make them uneconomical to harness. Thus, these resources are included in the discussion of available feedstocks but are not considered in the remainder of the report.

Fiber based (lignocellusic) ethanol production involves large quantities of feedstock. NREL uses a 2000 ton per day plant in its analysis which, at 85% capacity would require ~620,000 dry tons per year [23]. The low energy content of biomass feedstocks makes gathering and delivery costs extremely important. For biomass to ethanol conversion to be economical, the feedstock must be available in large quantities at a low price and in a central location. Data taken from the state biomass and bioenergy resource assessment is shown below in Table 1.

Table 1. 2002 summary of biomass resources and their degree of utilization in the State of Hawaii by county [22].

	tons yr^{-1}	Hawaii	Maui	Kauai	Honolulu
Swine Manure	Dry	410	540	180	1,560
Dairy Manure	Dry				8,300
Poultry	Dry	1,520[1]			4,830
Bagasse Fiber	Dry		275,000 (275,000)[2]	74,000 (56,000)[2]	
Cane Trash	Dry		137,000	37,000	
Pineapple Processing Waste	Dry		7,500 (7500)[2]		
Macadamia Nut Shells	Dry	19,000 (18,000)[2]			
Municipal Solid Waste	as-received	110,000	96,000	56,000	668,000 (600,000)[2,3]
Food Waste[4,5]	as-received	24,000	15,000	5,800	90,000
Sewage Sludge[5]	Dry	183	3,352 (3,352)[2,3]	246	16,576 (891)[2,3]
Fats/Oil/Grease	Dry	1,850	1,850	800	10,000

[1] combined poultry waste estimate for Hawaii, Maui, and Kauai.
[2] amount currently used.
[3] tipping fee associated with utilization.
[4] amount entering landfills.
[5] included in municipal solid waste value.

The largest sources of biomass wastes are bagasse, cane trash and MSW. As Table 1 shows, in most cases the large biomass waste streams are already being utilized. The largest waste streams, MSW on Oahu and bagasse on Maui, are used for power production at the HPOWER waste-to-energy plant and the HC&S factory, respectively. Excess bagasse is produced at the Gay & Robinson (G&R) sugar factory on Kauai and until recently was sold to a third party for power generation.

At both the HC&S plantation on Maui and the G&R plantation on Kauai, cane trash is burned in the field before harvesting. The feasibility of harvesting and processing the cane trash to capture the large fiber resource represented by this waste stream continues to be evaluated. If an economical method to harvest cane trash is developed this resource could be used to generate up to 10.5 million gallons per year using a conversion factor of 75 gallons of ethanol per dry ton developed by Shleser [6].

A recent BBI report concluded that MSW exists in a large enough quantity to justify a stand alone conversion plant on Oahu only. Production of 37 million gallons of ethanol per year was predicted under the assumption that the entire organic fraction was converted and that 1 dry ton of biomass would yield 60 gallons of ethanol [5]. In practice, the majority of this resource is presently being recycled, converted at HPOWER, or composted.

High electricity costs make power production a highly competitive use for biomass wastes. The recently mandated renewable portfolio standards, requiring that 10, 15, and 20%, of electricity sold in the state be generated from renewable sources by 2010, 2015, and 2020, respectively, will only increase competition for biomass feedstocks. An analysis performed in the Stillwater report demonstrates the economic advantage that biomass to electricity has over biomass to ethanol. Prospective biomass to ethanol plant developers would be competing with existing users of these fuel sources, likely driving up the feedstock cost.

Food waste is a subset of MSW, however its composition, primarily starch and sugar, makes it an excellent choice for ethanol conversion. Food waste resources were considered in the recent BBI report and findings showed that only Oahu could support an ethanol conversion facility based on this feedstock. Food waste generated on Oahu that enters the MSW stream was estimated to be ~135,000 tons with moisture content of ~70%. This resource could potentially generate ~2.5 MGPY of ethanol [21]. Residential food waste is not currently source separated from MSW and is therefore not currently available for conversion to ethanol. A portion of the food waste stream generated at commercial establishments is separated but is largely used as swine feed [25].

5.2 Potential Feedstocks

The potential for producing dedicated biomass energy crops on agricultural lands has been studied, but generally only for specific locations or crops [7, 9, 19, 21, 26, 27, 28]. Determining mid- to long-term ethanol production potential requires a comprehensive investigation of probable and possible biomass energy crop supplies.

Hawaii has excellent environmental conditions for energy crop production and a substantial amount of land suitable for agriculture. A year round growing season and strong solar insolation generate high yields from a variety of tree and grass crops. Identification and study of high yielding energy crops suitable for cultivation in Hawaii has been carried out over the last 20-30 years. The most promising crops for fiber production include grass crops; *Saccharum officinarum* (sugar cane), *Pennisetum purpureum* (banagrass), and woody crops, *Eucalyptus grandis, Eucalyptus saligna*, and *Leucaena leucocephala* (giant *Leucaena* or haole koa). These are the most likely candidates for dedicated energy crops for sugar or fiber production and have been studied to the greatest extent. Other crops, sweet sorghum, albizia, guineagrass, etc, have been proposed but large scale trials to evaluate their suitability as energy crops have not been carried out in Hawaii. Sugar cane, banagrass, *E. grandis*, *E. saligna* and giant *Leucaena* were considered in the present study. Of the selected crops, only sugar cane and *Eucalyptus* are being grown commercially. Large acreages of eucalyptus have been planted but none have been harvested to date.

5.2.1 Sugar Cane

Sugar cane has a long history of cultivation in Hawaii dating back to the 1800's. Historical data on yields, management practices, cost of production and planted acreage are available in the literature [29].

In Hawaii, sugar cane is grown to produce sugar, and molasses and bagasse are generated as byproducts. Molasses is marketed as cattle feed supplement, but is being considered as a feedstock for ethanol conversion. Bagasse is used to fuel boiler systems that generate steam and electricity to run the factory – the latter may also be exported to the utility.

In Brazil, where ethanol production from sugar cane is common practice, factories are set up to process cane juice into sugar and molasses, or ethanol, or some mixture of the two products, depending on market prices. If sugar cane were to be grown as a dedicated energy crop in Hawaii, Brazilian production could be considered as a model.

A large portion of fiber generated during the growth cycle, commonly called cane trash, is burned off in the field prior to harvest. This could provide additional fiber for conversion to ethanol if it could be economically recovered and lignocellulosic conversion technologies become commercial.

The high yield and variety of products that can be generated using sugar cane make it an obvious candidate energy crop to be considered in this report. It also has the advantage of being an established crop in Hawaii with an infrastructure and labor force already in place. The modification and expansion of existing sugar operations to meet ethanol demands is one of the most likely avenues for commercial ethanol production in the state.

For all of its advantages, sugar cane as an energy crop is not without draw backs. Chief among them are high irrigation requirements and cost competitive production of sugar and molasses elsewhere in the world. High costs of labor, land, fertilizer and water put added stress on the sugar industry in Hawaii. A suitable method for the disposal of vinasse, the liquid effluent from distillery operations, will also need to be identified. Nonetheless, as the only established crop of those selected, sugar cane deserves to be placed at the top of the list of potential dedicated energy crops.

5.2.2 Banagrass

Banagrass was introduced to Hawaii from Australia in the mid-1970's to be used as an indicator plant for ratoon stunting disease in sugar cane. Banagrass is a high yielding, upright grass species recognized for its potential as a biomass energy crop. Banagrass ratoons well with a number of trials showing repeatedly high yields from successive crops.

Banagrass is considered to be very close to sugar cane in management and harvesting requirements, although its management as a energy crop would be different from that of today's sugar operations in Hawaii. In our analysis, banagrass production is based on sugar cane cultural practices, but with fiber as the only product. Banagrass has higher dry biomass yields and is assumed to be grown on an eight month harvesting cycle. A number of trials have been conducted in Hawaii to estimate yield and to develop management techniques. Data from various trials can be found in the report entitled, *Investigation of Biomass-for-Energy Production on Molokai* [19]. This report also includes information on harvest methods and projected production costs. Banagrass was planted as a dedicated energy crop for power generation on former sugar lands at the Waialua Sugar Company plantation on Oahu but the project was abandoned before completion of the first crop cycle. Unfortunately, no production data are available from this effort.

5.2.3 *Eucalyptus*

Eucalyptus was introduced to Hawaii in the 1870's and planted to protect denuded watersheds. It was first commercially planted as a source of fuel for boilers in the sugar industry. While the trees flourished in the tropical environment, difficulties with harvesting and advances in bagasse handling and boiler technologies made it an uneconomic fuel. Other varieties were introduced over the following century and used for wind breaks, erosion mitigation, and in forestry experiments. In the last ten to fifteen years *Eucalyptus* plantations have been established on the island of Hawaii, with over 25,000 acres presently being managed intensively.

Extensive work on species selection and growth characterization was done in the 1980's by the BioEnergy Development Corporation, a subsidiary of C. Brewer [13]. Other trials were conducted at locations across the state by the Department of Land and Natural Resources, Hawaii Agriculture Research Center, and the University of Hawaii.

Unlike traditional forest plantings which try to maximize merchantable timber production, intensively-cultured, short-rotation plantations seek to maximize biomass production. Plantations are generally planned to operate on a 5-8 year rotation. *Eucalyptus* species that have been studied in Hawaii and have been recommended for this purpose include *E. saligna, E. grandis, E. robusta, E. globulus*, and *E. urophylla*. The two species chosen for consideration in this report are *E. saligna* and *E. grandis*, which both show excellent yields over a range of environments. The other varieties outperform only in certain niche environments, very high elevation, poorly drained soil, very low rainfall, etc.

The existence of commercial plantings of *Eucalyptus* will yield valuable experience and information to future developers of dedicated energy crops. These first commercial operations will also help to develop the skilled local labor force that will be required if larger plantings are to be successful.

5.2.4 *Leucaena leucocephala* (giant Leucaena)

Giant *Leucaena* was first brought to prominence and tested in Hawaii by Dr. James Brewbaker at the University of Hawaii during the 1970's. Since then the University of Hawaii has developed varieties and provided seeds to researchers throughout the world. Trials in Hawaii were conducted on Oahu and Molokai. Information on harvesting methods and yield projections can be found in a report titled, *Giant Leucaena Energy Tree Farm* [26].

6. Land Analysis

Hawaii has a long agricultural history, with sugar and pineapple plantations dating back into the 1800's. While times have changed, and many agricultural lands have been taken out of production, nearly half of the land in the state, 1,928,034 acres, is zoned for agriculture [30]. Land use and zoning in Hawaii follow strict guidelines set forth in the State Land Use Law enacted in 1961.

There are four zoning designations in the State of Hawaii, Agriculture, Rural, Urban and Conservation. In an earlier analysis of land availability conducted in 1992, Urban and Rural lands were considered unavailable, conservation lands were considered probably available and agricultural lands were considered available [31] for energy crop production. In this analysis only lands zoned for agriculture will be considered. Out of the total lands zoned for agriculture, about half, 977,043 acres, are categorized as agricultural lands important to the State of Hawaii (ALISH). The State of Hawaii (SOH) owned lands zoned for agriculture account for about 430,000 acres or 22% of the total agriculturally zoned lands. Of the 1.93 million acres zoned for agriculture, 1.30 million are considered to be in farming with the majority of these lands fallow or used for grazing. Only 104,000 acres of the 1.30 million acres of farmland were actually in crops during 2004 [32].

6.1 Energy Crop Suitability

An understanding of statewide land suitability for growing energy crops and the types of crops that can be grown on any given parcel is useful information for biofuels production planning. Data on soil types, slopes, and rainfall are available and can be used in screening strategies to determine whether lands are potentially suitable for energy crop production. Using geographic information systems (GIS) software [33], different screening criteria were overlaid to assess the suitability and potential availability of lands for dedicated energy crop production.

Soil series maps available through the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) were used in the land analysis. These maps include soil type names and descriptions and information on slope, irrigated or unirrigated use, and suitability for sugar cane, pineapple, pasture, and woodland uses. Unirrigated refers to lands and crops that are wholly rainfed (naturally irrigated) and irrigated refers to lands and crops that receive some form of mechanically applied water to supplement rainfall. Other GIS data including annual rainfall, land use zoning, land ownership including a category for large land owners (LLO), and agricultural lands of importance to the State of Hawaii (ALISH) are available through the Hawaii statewide GIS program website (see http://www.hawaii.gov/dbedt/gis/).

The soil series maps from NRCS are accompanied by several informative guides. *Guide to Mapping Units*, includes tables of soil series designators and their suitability for sugar cane, pineapple, pasture and woodland uses [34]. Another such guide titled, *Use and Management of the Soils*, provides details on limitations and management needs of the soil groups described in the series maps [35].

Based on the energy crops identified in potential feedstock analysis, the soil types that were suitable for sugar cane and woodland production were selected and mapped using GIS software. This provided an island by island breakdown of acreage suitable for sugar cane and woody biomass crops based on soil types. This screening process does not provide a high degree of specificity but allows potential production scenarios to be evaluated relatively easily.

Because slope is an important factor in harvesting and management regimes, as well as erosion considerations, the suitable soils were further divided into three slope ranges, ≤ 10%, 10% to 20%, and >20%. The slope ranges provided for the NRCS soil series vary widely, so the midpoint of the range was used to place them in these slope categories. For example the soil mapping unit, EaC, Ewa silty clay loam, has a slope range of 6 to 12% and a midpoint of 9, which puts it in the slope ≤10% category.

Following the soil and slope analyses, water available through rainfall was evaluated. The selected crops have varying water requirements. Sugar cane and banagrass require abundant water to reach maximum yields, while *Eucalyptus* and *Leucaena* can be grown with lesser amounts. Water resources are limited in many areas due to increased urban and residential demand and the need to maintain stream flows to preserve environmental quality. The quantity of water available to developers of dedicated energy crops remains undetermined. For this reason, an analysis of potential rain fed areas was conducted. Historically, many of the sugar plantations on Hawaii and some on Kauai were unirrigated. Using data from the Hawaii Sugar Manual and the GIS annual rainfall layer, a minimum level of approximately 70 inches per year was established for unirrigated sugar production [29]. The GIS annual rainfall data included an isopleth at 78 inches and this was used in the analysis as the minimum rainfall required for unirrigated sugar cane production.

It was assumed that *Eucalyptus* and *Leucaena* would be grown without irrigation but that minimum levels of rainfall would be required. *Eucalyptus* was chosen for areas with soil types suitable for woodland species and rainfall levels of 40 inches or more. This level of rainfall is close to the lowest level reported for trials in Hawaii carried out by the BioEnergy Development Corporation [13]. While certain *Eucalyptus* cultivars might grow well even at lower rainfall levels, they have not been tested extensively in Hawaii.

In the NRCS *Use and Management of the Soils* guide, *Leucaena* is reported as growing well in areas with 25-60 inches of rainfall [35]. Since *Eucalyptus* has seen greater study and has an established base of uses other than as fuel, it was given priority over *Leucaena* in areas where both could be grown. For this reason, Leucaena was selected for regions with woodland soil types and annual rainfall of 20 to 40 inches. The GIS annual rainfall data included an isopleth at 20 inches and this was used as the minimum rainfall required for *Leucaena* production.

Combining the soil, slope and rainfall evaluations completed the energy crop suitability portion of the land analysis. The resulting maps and tables identify all the lands suitable for growing the four energy crops selected in the potential feedstock analysis. While land areas identified in this analysis are suitable for growing energy crops according to the screening criteria described above, the analysis does not address issues of economics or preferred use for any particular parcel of land. Determining the economic feasibility of energy crop production in a specific location would involve more extensive analysis. The current work is a preliminary effort that will help identify potential locations for energy crop production. The remainder of the analysis is focused on potential land availability.

7. Potential Ethanol Production in Hawaii

Four crop scenarios are presented; 1) sugar cane grown on all soils suitable for sugar, 2) *Eucalyptus* and *Leucaena* grown on all soils suitable for trees, 3) sugar cane given first priority, grown on all soils suitable for sugar, and *Eucalyptus* and *Leucaena* given second priority, grown on remaining soils suitable for trees, and 4) banagrass grown on all soils suitable for sugar. Results of each for each crop scenario are presented below.

7.1 Sugar

Table 2 summarizes land acreages that NRCS identifies as having soil mapping units in the sugar land capability group. For example, the Alae soil series comprises three mapping units;

1) Alae cobbly sandy loam, 0 to 3% slope
2) Alae cobbly sandy loam, 3 to 7% slope
3) Alae sandy loam, 3 to 7% slope

All of these are identified as being suitable for sugar cane production.

Distribution of the land areas of NRCS sugar soils that are zoned agricultural on each island is shown in the maps labeled Figures 1 to 6. Colors on the maps indicate slope and rainfall categories used in Tables 2 and 3. Note that only the island of Hawaii has land areas in all three slope and both annual rainfall categories and therefore six map colors are required. Maui, Lanai, Molokai, and Oahu do not have NRCS sugar soils that are zoned agricultural with annual rainfall above 78 inches. Maps for these islands require only two colors to differentiate slopes. Kauai has two slope and two rainfall categories as shown in the four color map.

Soil slopes in Table 2 are classified as 0 to 10%, 10 to 20%, and >20% and acreages in each group are presented by island. The data in Table 2 and a series of tables that follow are all arranged in the same manner and a description is provided here. The first data column in the table contains values for NRCS sugar soils (NRCS-SS). The second data column is a subset of the first column showing the acreage of the NRCS sugar soils (SS) that are zoned for agricultural

(ZA) use (NRCS-SS-ZA). The third, fourth and fifth columns are each subsets of the second column based on land designation. The third column shows acreage of NRCS sugar soils that are zoned for agricultural use and are owned by the State of Hawaii (NRCS-SS-ZA-SOH). The fourth column shows acreage of NRCS sugar soils that are zoned for agricultural use and are owned by large land owners (NRCS-SS-ZA-LLO). Note that the SOH lands are included in the LLO category. The fifth column shows acreage of NRCS sugar soils zoned for agriculture that are also categorized as agricultural lands of importance to the State of Hawaii (NRCS-SS-ZA-ALISH).

Table 2. Acreages of NRCS sugar soils by land designation and slope.

	Natural Resources Conservation Service, Sugar Soils				
	Total	Zoned Ag	Zoned Ag, State Owned	Zoned Ag, Large Land Owners	Zoned Ag, ALISH
Island	acres	acres	acres	acres	acres
Hawaii	163,066	135,283	15,104	66,801	124,877
0-10% slope	86,640	68,612	7,136	28,648	64,356
10-20% slope	57,801	49,222	6,209	28,453	44,832
20%+ slope	18,624	17,448	1,759	9,700	15,689
Maui	69,707	59,108	3,191	50,547	57,564
0-10% slope	50,654	43,179	2,311	39,369	42,177
10-20% slope	19,053	15,928	880	11,178	15,388
20%+ slope	0	0	0	0	0
Lanai	12,142	9,894	10	9,884	8,961
0-10% slope	10,022	8,128	10	8,120	7,691
10-20% slope	2,120	1,766	0	1,764	1,270
20%+ slope	0	0	0	0	0
Molokai	21,573	19,455	7,242	18,005	16,527
0-10% slope	15,429	13,396	6,004	12,145	11,245
10-20% slope	6,144	6,059	1,238	5,860	5,283
20%+ slope	0	0	0	0	0
Oahu	117,233	62,509	4,022	51,112	54,734
0-10% slope	101,540	54,003	3,322	43,561	47,099
10-20% slope	15,693	8,506	700	7,551	7,635
20%+ slope	0	0	0	0	0
Kauai	95,208	74,077	21,258	55,795	66,856
0-10% slope	68,893	53,729	15,367	40,483	49,687
10-20% slope	26,316	20,348	5,891	15,312	17,169
20%+ slope	0	0	0	0	0
State Total	478,929	360,324	50,828	252,145	329,520
0-10% slope	333,178	241,048	34,150	172,327	222,254
10-20% slope	127,127	101,829	14,918	70,118	91,576
20%+ slope	18,624	17,448	1,759	9,700	15,689

Statewide there are more than 360,000 acres of NRCS-SS-ZA land and more than one third are on the island of Hawaii. This classification includes areas on Maui, Kauai, and Oahu in the range of 60,000 to 75,000 acres each. This pattern of distribution between islands is similar for the NRCS-SS-ZA ALISH lands, although the total is smaller, about 330,000 acres. On all islands, the SOH owns ~50,000 acres with more than 20,000 on Kauai and 15,000 on Hawaii. LLO lands total 250,000 acres and are relatively evenly distributed between Hawaii, Maui, Oahu, and Kauai. Table 3 presents the sugar cane acreage in Hawaii in 1969 near the peak of the sugar industry compared with the acreage for potential production identified in the present study.

Table 3. Comparison of potential sugar cane acreage with historic use [29].

Island	1969 Sugar Cane Acres	Potential Sugar Cane Acres, Present Study, NRCS-SS-ZA
Hawaii	107,519	135,283
Maui	52,263	59,108
Oahu	44,937	62,509
Kauai	37,497	74,077
Total	242,216	330,977

7.1.1 Slope

Two thirds of the 360,000 acres of NRCS-SS-ZA have slopes of less than 10% and Hawaii, Maui, Oahu, and Kauai each have areas in the range of 43,000 to 68,000 acres in this grouping. NRCS-SS-ZA with slopes greater than 20% total 17,000+ acres and all are located on Hawaii. The remaining lands with slopes of 10 to 20% total 100,000 acres with half on Hawaii.

7.1.2 Rainfall/Irrigation Requirements

Sugar in Hawaii has been grown on lands receiving varying amounts of rainfall. The land area data sets from Table 2 are further characterized according to their annual rainfall as shown in Table 4. Historically, sugar has been grown on lands receiving more than 70" of annual rainfall without supplemental irrigation. Land receiving less annual rainfall usually was irrigated or partially irrigated for sugar production. The NRCS-SS-ZA lands from Table 2 were categorized according to annual rainfall amounts, either greater or less than 78". This value was chosen because a 78" isopleth was included in the State of Hawaii GIS data sets. Of the 360,000 acres of NRCS-SS-ZA soils in the state, 70% would require irrigation. The distribution between islands is not equal – all NRCS-SS-ZA soils on Maui, Lanai, Molokai, and Oahu require irrigation. Sugar soils on the islands of Hawaii and Kauai that receive rainfall above 78" account for 70% and 20% of each island's NRCS-SS-ZA total, respectively. Similar percentages are observed for the NRCS-SS-ZA SOH, LLO, and ALISH categories with variations of less than 10% (absolute) from the overall NRCS-SS-ZA distribution.

7.1.3 Ethanol Potential

Historic yields from irrigated and unirrigated sugar cane crops were used to estimate amounts of fermentable sugars that could be produced from the sugar soil acreages shown in Table 4. Hawaii Sugar Manual [29] sugar yield and acreage data for thirteen plantations from 1975-1992 were used in these calculations and are summarized in Table 5. Six plantations on Hawaii were used to determine the average unirrigated yield. Unirrigated land in production on these plantations ranged from 69 to 100% with an average of 90%. Yield data from seven plantations, three located on Kauai, three on Maui, and one on Oahu, with 100% irrigated lands were used to determine the average irrigated sugar cane yield. Raw sugar yields of 6.4 and 4.2 tons per acre per year were calculated for irrigated and unirrigated crops, respectively.

Molasses contains sugars that cannot be economically recovered during processing. The Hawaii sugar industry historically produces 0.276 tons of molasses for every ton of raw sugar produced. The fermentable sugar content of molasses was assumed to 48.2% by weight, based on unpublished data provided by HC&S [41]. Thus sugar yields were calculated by multiplying the acreages in Table 4 by raw sugar yield factors.

Table 4. Potential irrigated (<78") and unirrigated (>78") acreages of agriculturally zoned NRCS sugar soils by land designation.

	Zoned Ag		Zoned Ag, State Owned		Zoned Ag, Large Land Owners		Zoned Ag, ALISH	
Annual Rainfall	<78"	>78"	<78"	>78"	<78"	>78"	<78"	>78"
Island	acres	acres	acres	acres	acres	acres	acres	acres
Hawaii	40,393	94,890	4,044	11,060	25,442	41,358	38,698	86,179
Maui	59,108	0	3,191	0	50,547	0	57,564	0
Lanai	9,894	0	10	0	9,884	0	8,961	0
Molokai	19,455	0	7,242	0	18,005	0	16,527	0
Oahu	62,509	0	4,022	0	51,112	0	54,734	0
Kauai	60,574	13,503	18,831	2,427	47,269	8,526	55,532	11,324
State Total	251,932	108,393	37,340	13,487	202,260	49,885	232,016	97,504

Table 5. Historic irrigation data and average yields for selected plantations in Hawaii from 1975 to 1992 [29].

Plantation	% Unirrigated	Raw Sugar Yield[1] tons/acre	Raw Sugar Yield[2] tons/acre/year
Davies Hamakua Sugar Co	80	10.2	4.1
Honokaa Sugar	69	10.1	4.3
Hawaiian Agriculture (Ka'u)	100	11.2	4.0
Laupahoehoe Sugar	93	10.3	4.2
Mauna Kea Sugar	100	10.5	4.9
Puna Sugar	100	8.8	3.9
Gay & Robinson	0	14.2	7.1
Kekaha Sugar	0	13.0	6.3
Olokele Sugar	0	13.0	6.5
Hawaiian Commercial & Sugar	0	12.7	6.0
Pioneer Mill	0	12.0	6.2
Wailuku Sugar	0	12.0	6.2
Oahu Sugar	0	12.4	6.6

[1] raw sugar yield based on raw sugar produced divided by acres harvested
[2] annualized raw sugar yield based on raw sugar produced divided by acres harvested divided by age of crop in years

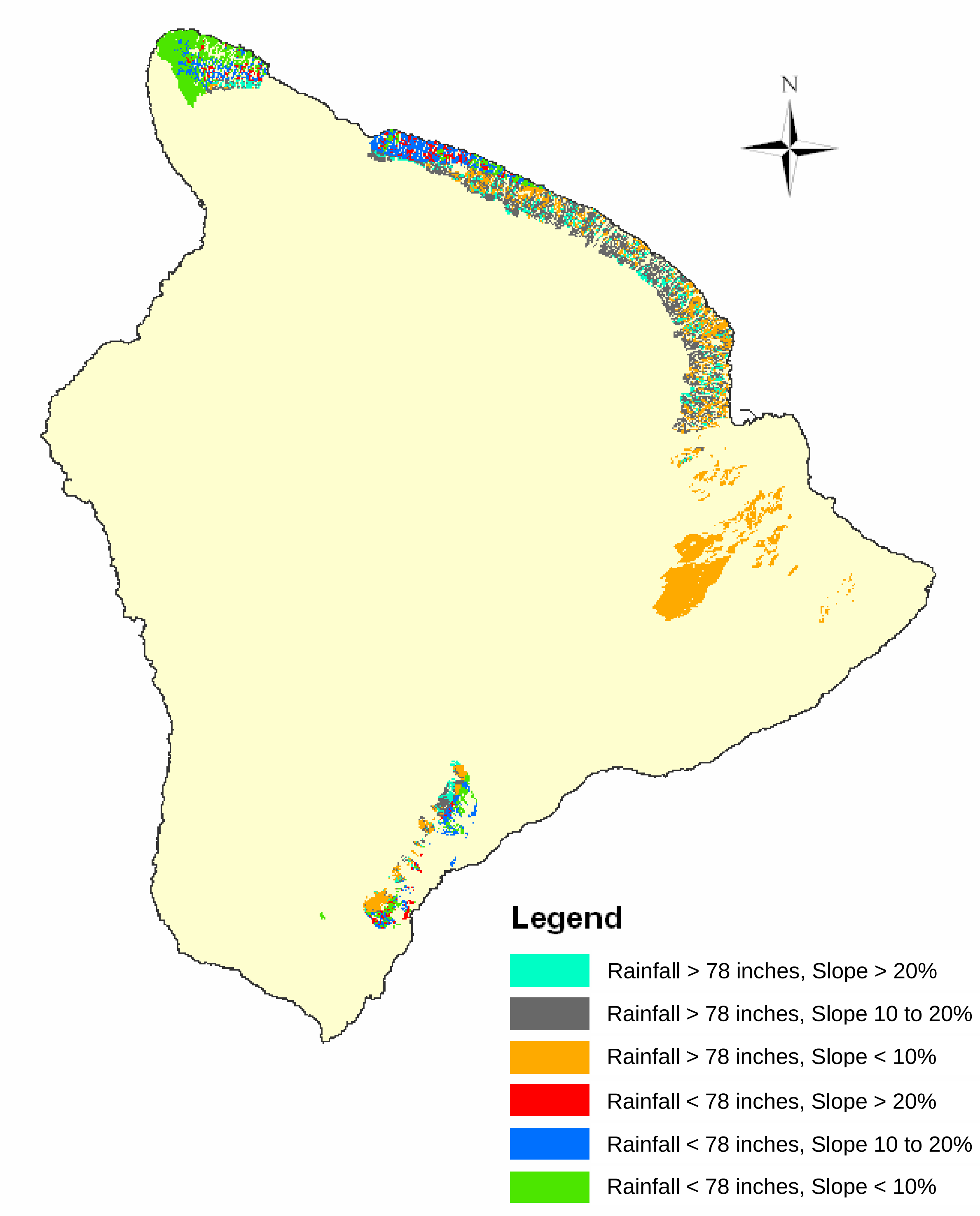

Figure 1. Map of NRCS sugar soils zoned agricultural on the island of Hawaii showing rainfall and slope classifications.

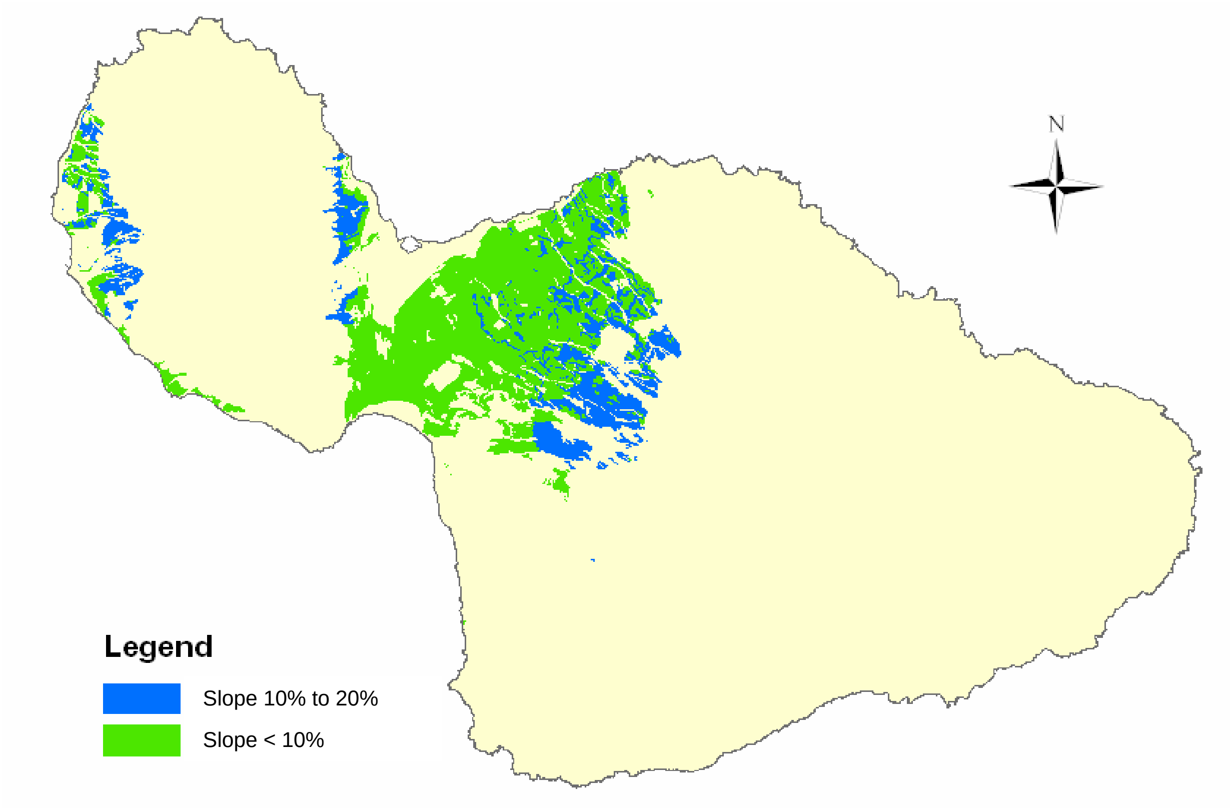

Figure 2. Map of NRCS sugar soils zoned agricultural on the island of Maui showing slope classifications.

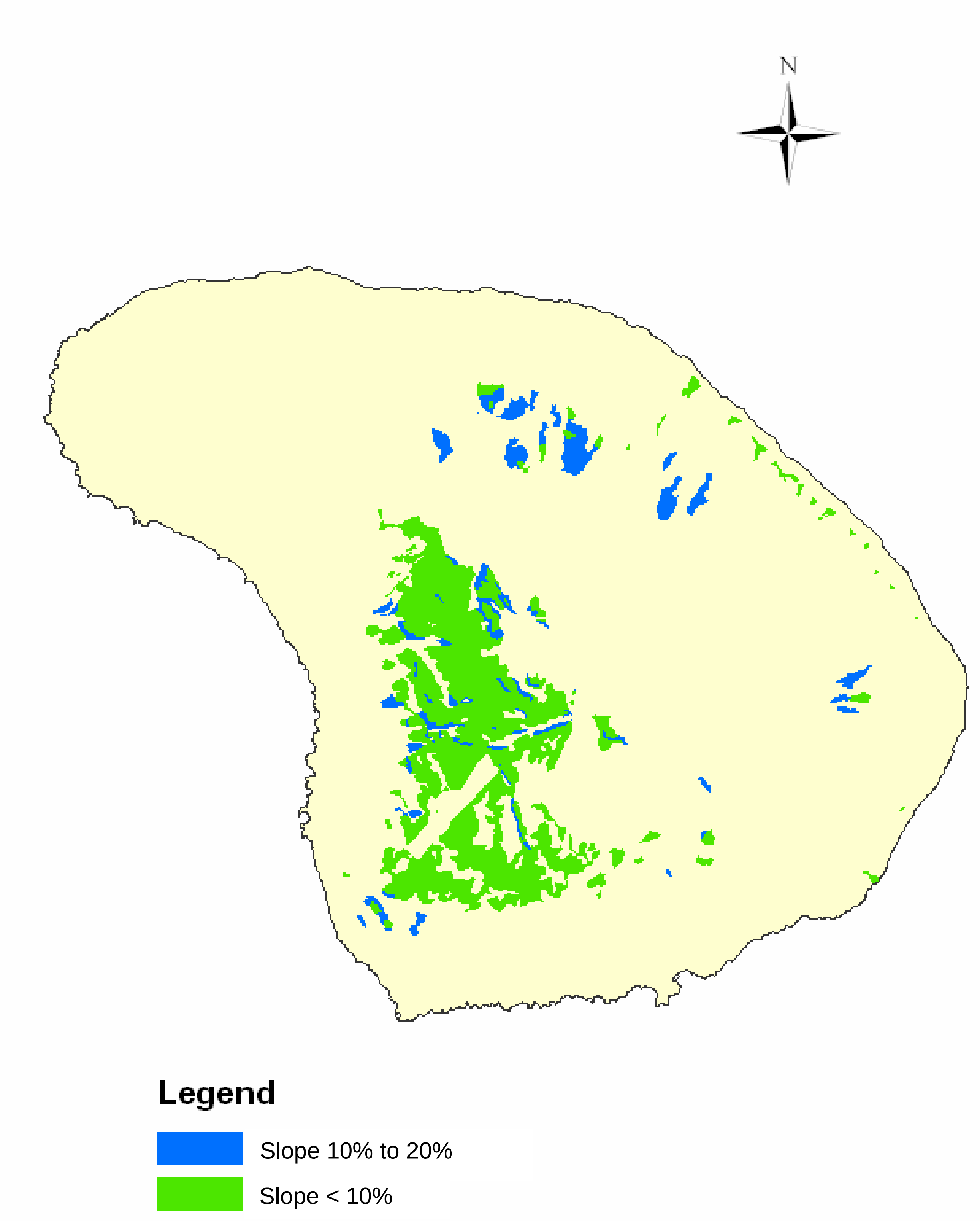

Figure 3. Map of NRCS sugar soils zoned agricultural on the island of Lanai showing slope classifications.

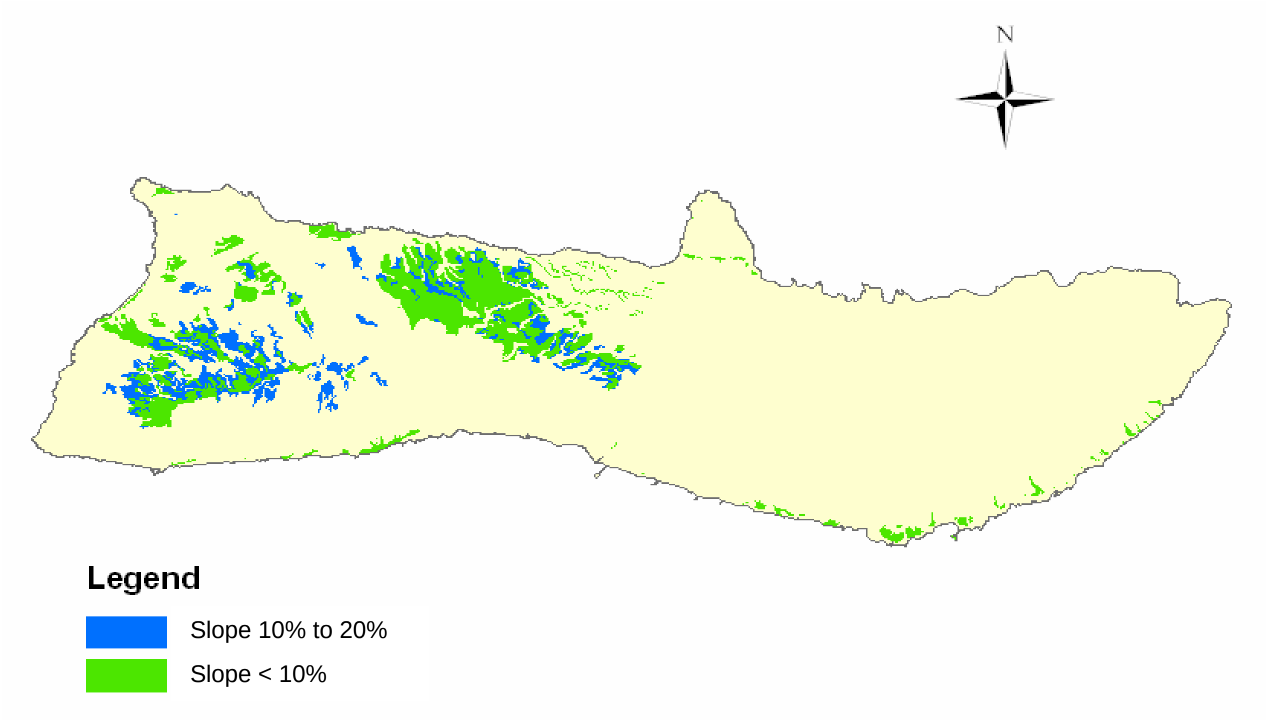

Figure 4. Map of NRCS sugar soils zoned agricultural on the island of Molokai showing slope classifications.

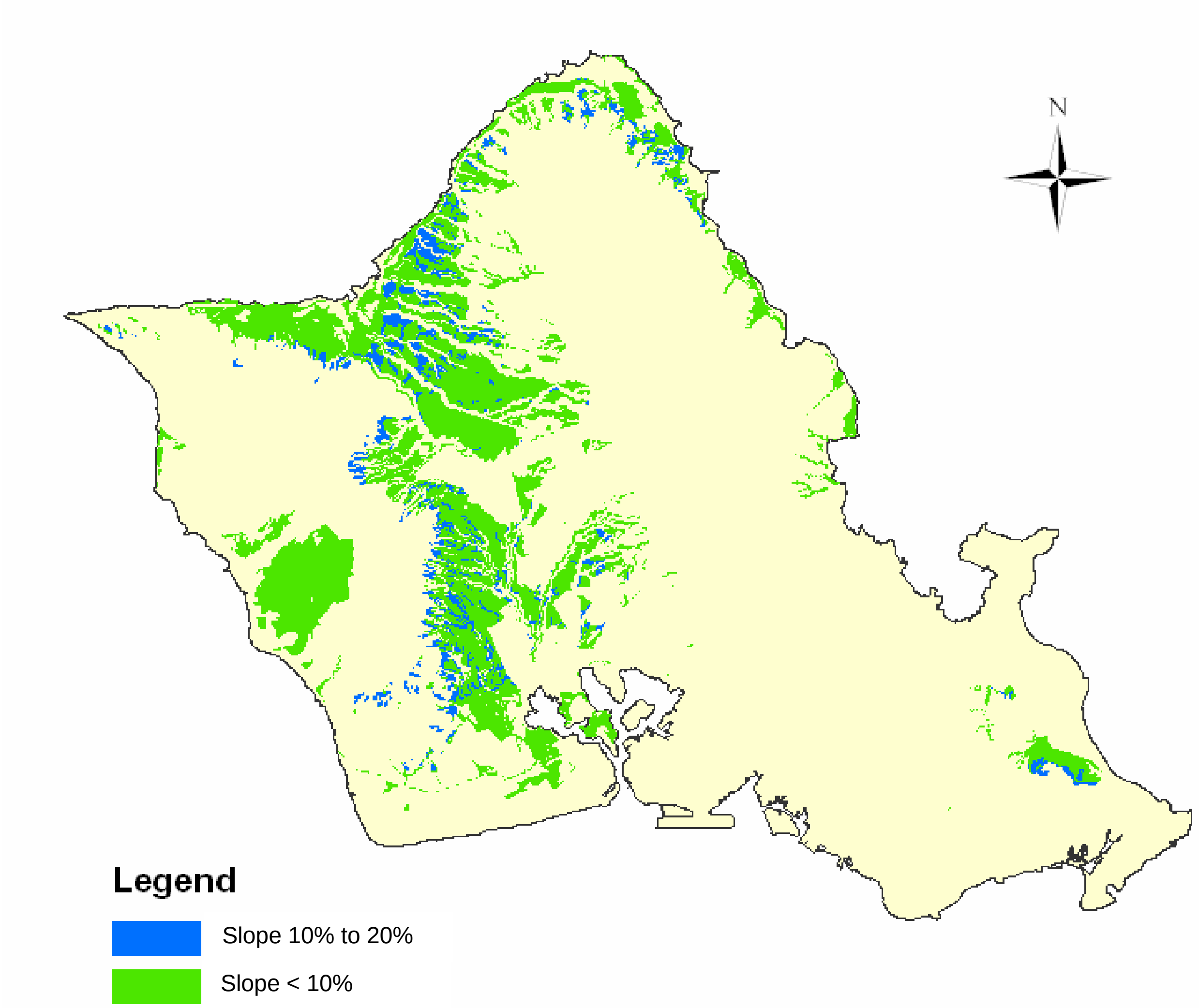

Figure 5. Map of NRCS sugar soils zoned agricultural on the island of Oahu showing slope classifications.

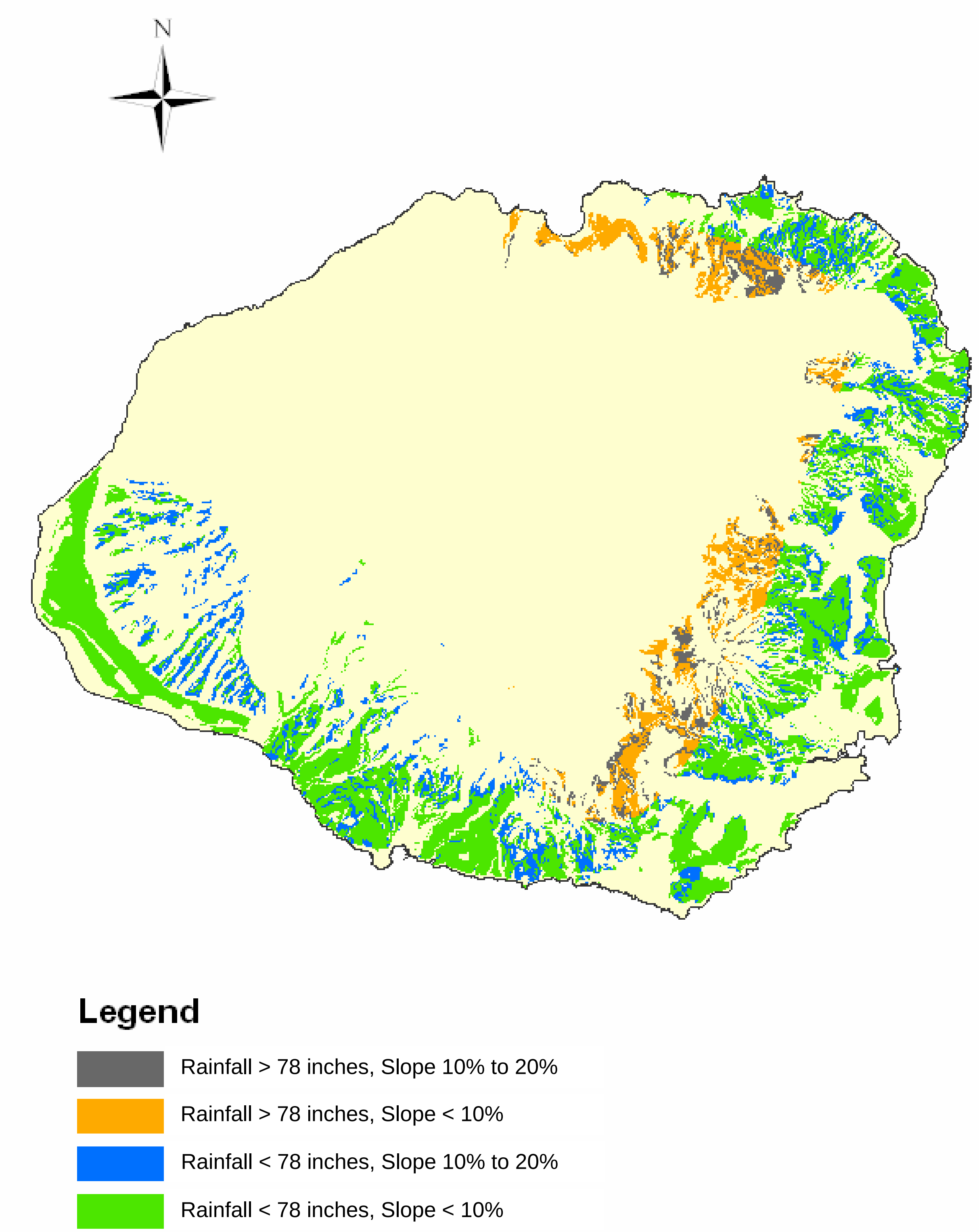

Figure 6. Map of NRCS sugar soils zoned agricultural on the island of Kauai showing slope classifications.

$$\frac{tons\ \ fermentable\ sugar}{year} =$$

$$acres\ x\ \frac{tons\ raw\ sugar}{acre\ year}$$

$$x\left(\left(\frac{0.96\ tons\ \ ferm.\ sugar}{ton\ raw\ sugar}\right) + \left(\frac{0.276\ ton\ molasses}{ton\ raw\ sugar}\ x\ \frac{0.482\ tons\ \ ferm.\ sugar}{ton\ molasses}\right)\right)$$

A conversion of 141 gallons of ethanol per ton of fermentable sugars [42] was applied to the resulting fermentable sugar total to arrive at a potential ethanol yield as shown in Table 6.

In addition to fermentable sugars, sugar cane produces fiber at a ratio of roughly 1.5 tons fiber per ton of fermentable sugar [43]. This assumes that the sugar cane fields have not been burned prior to harvest as is currently the case for most sugar produced in Hawaii. Energy demands (electricity and process heat) of an autonomous distillery based on fermentable sugars from sugar cane would be expected to consume 0.9 tons of fiber per ton of fermentable sugars, leaving 0.6 tons of fiber per ton of fermentable sugars available for other uses [44]. Fiber is composed of cellulose, hemicellulose, and lignin. Both cellulose and hemicellulose can be hydrolyzed into simple sugars that can be fermented to produce ethanol. This technology has been demonstrated at the pilot scale and, although not yet commercial, is expected to be brought to the market in the near future. An estimate of 70 gallons of ethanol per ton of fiber based on best available production data and estimates of reasonable yield improvements was used to project potential ethanol production from surplus fiber [23, 45].

$$\frac{gal\ \ EtOH}{yr} = \left(\frac{tons\ \ fermentable\ sugars}{yr}\right) x \left(\frac{0.6\ tons\ \ fiber}{tons\ \ fermentable\ sugars}\right) x \left(\frac{70\ gal\ \ EtOH}{ton\ \ fiber}\right)$$

The results of this calculation are shown in Table 7 and the total potential ethanol production from sugar cane (fermentable sugars and fiber) is presented in Table 8. In addition, a co-product of 2.3 kWh of surplus electricity is produced per gallon of ethanol from fiber. Lignin, methane from treatment of wastewater digestion, and other combustibles are converted to steam in a boiler and this electricity surplus is projected after meeting energy demands at the lignocellulosic ethanol production facility [23]. Potential electricity production values are summarized in Table 8.

NCRS-SS-ZA lands have the potential to produce 428 million gallons of ethanol and 226 million kWh per year using sugar and fiber from sugarcane. Subsets of this land area will produce accordingly lesser amounts of both products. SOH, LLO, and ALISH lands have the potential to produce 61, 311, and 392 million gallons of ethanol, respectively. Associated electricity production is shown to equal 0.53 kWh per gallon of total ethanol production, i.e. from fermentable sugars and fiber (226 million kWh/428 million gal ethanol).

Table 8 also includes electricity sales and gasoline sales as ethanol equivalent by island for 2005 [46]. Ethanol has two thirds the energy of gasoline on a volume basis and this factor was used to convert gallons of gasoline to gallon of ethanol equivalent. The data show that utilizing all of the NRCS-SS-ZA lands would not have the potential to produce enough ethanol to completely displace current gasoline use statewide, however, Hawaii, Maui, and Kauai counties collectively could potentially produce enough to match their current gasoline energy demand using NRCS-SS-ZA or NRCS-SS-ZA ALISH lands. Maui and Kauai counties could also potentially meet gasoline demand with ethanol produced from sugar cane on NRCS-SS-ZA LLO lands and Kauai would have a surplus of 28 million gallons. Total potential ethanol production from NRCS-SS-ZA LLO lands would equal 45% of the 2005 state usage. Total potential production from NRCS-SS-ZA SOH lands equal 8.8% of the 2005 gasoline demand.

The greatest potential for production of byproduct electricity, 72 million kWh per year, is on Hawaii from sugar cane grown on NRCS-SS-ZA lands. This amounts to about 6% of total power sales on Hawaii in 2005. Byproduct electricity from NRCS-SS-ZA lands as percentage of 2005 power sales on Maui and Oahu are 3.5 and 0.5%, respectively. Byproduct electricity values from sugar cane grown on NRCS-SS-ZA lands on Kauai, Lanai, and Molokai, islands with lower electricity usage, range from 10 to 35% of 2005 sales. Potential byproduct electricity from SOH, LLO, and ALISH designations would be reduced in accordance with their lower land areas.

Table 6. Ethanol potential from fermentable sugars from sugar cane grown on irrigated and unirrigated acreages of agriculturally zoned NRCS sugar soils by land designation.

	Zoned Ag			Zoned Ag, State Owned			Zoned Ag, Large Land Owners			Zoned Ag, ALISH		
Annual Rainfall	<78"	>78"		<78"	>78"		<78"	>78"		<78"	>78"	
	Irr.	Unirr.	Total	Irr.	Unirr.	Total	Irr.	Unirr.	Total	Irr.	Unirr.	Total
Island	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr
Hawaii	41.3	63.7	105.0	4.1	7.4	11.6	26.0	27.7	53.8	39.6	57.8	97.4
Maui	60.4	0.0	60.4	3.3	0.0	3.3	51.7	0.0	51.7	58.9	0.0	58.9
Lanai	10.1	0.0	10.1	0.01	0.0	0.0	10.1	0.0	10.1	9.2	0.0	9.2
Molokai	19.9	0.0	19.9	7.4	0.0	7.4	18.4	0.0	18.4	16.9	0.0	16.9
Oahu	63.9	0.0	63.9	4.1	0.0	4.1	52.3	0.0	52.3	56.0	0.0	56.0
Kauai	61.9	9.1	71.0	19.3	1.6	20.9	48.3	5.7	54.0	56.8	7.6	64.4
State Total	257.6	72.7	330.3	38.2	9.0	47.2	206.8	33.5	240.3	237.2	65.4	302.6

Table 7. Ethanol potential from sugar cane fiber grown on irrigated and unirrigated acreages of agriculturally zoned NRCS sugar soils by land designation.

	Zoned Ag			Zoned Ag, State Owned			Zoned Ag, Large Land Owners			Zoned Ag, ALISH		
Annual Rainfall	<78"	>78"		<78"	>78"		<78"	>78"		<78"	>78"	
	Irr.	Unirr.	Total	Irr.	Unirr.	Total	Irr.	Unirr.	Total	Irr.	Unirr.	Total
Island	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr	million gal/yr
Hawaii	12.3	19.0	31.3	1.2	2.2	3.4	7.7	8.3	16.0	11.8	17.2	29.0
Maui	18.0	0.0	18.0	1.0	0.0	1.0	15.4	0.0	15.4	17.5	0.0	17.5
Lanai	3.0	0.0	3.0	0.003	0.0	0.003	3.0	0.0	3.0	2.7	0.0	2.7
Molokai	5.9	0.0	5.9	2.2	0.0	2.2	5.5	0.0	5.5	5.0	0.0	5.0
Oahu	19.0	0.0	19.0	1.2	0.0	1.2	15.6	0.0	15.6	16.7	0.0	16.7
Kauai	18.4	2.7	21.1	5.7	0.5	6.2	14.4	1.7	16.1	16.9	2.3	19.2
State Total	76.7	21.7	98.4	11.4	2.7	14.1	61.6	10.0	71.6	70.7	19.5	90.1

Table 8. Ethanol and electricity potential from sugar cane grown on agriculturally zoned NRCS sugar soils by land designation compared with actual usage.

Island	Zoned Ag		Zoned Ag, State Owned		Zoned Ag, Large Land Owners		Zoned Ag, ALISH		Actual Usage in 2005[1]	
	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	Gasoline million gal/yr as ethanol equivalent[2]	million kWhr/yr
Hawaii	136.2	71.9	15.0	7.9	69.8	36.8	126.4	66.7	112	1,116
Maui	78.4	41.4	4.2	2.2	67.1	35.4	76.4	40.3	94	1,188
Lanai	13.1	6.9	0.0	0.0	13.1	6.9	11.9	6.3	-	28
Molokai	25.8	13.6	9.6	5.1	23.9	12.6	21.9	11.6	-	36
Oahu	82.9	43.8	5.3	2.8	67.8	35.8	72.6	38.3	440	7,721
Kauai	92.1	48.6	27.1	14.3	70.1	37.0	83.5	44.1	42	449
State Total	428.7	226.3	61.3	32.4	311.8	164.6	392.8	207.3	688	10,539

[1] Data from Hawaii Energy Data Book, http://www.hawaii.gov/dbedt/info/economic/databook/db2005/

[2] Gasoline sales by county converted to ethanol equivalent; 1 gal ethanol = 0.66 gal gasoline

7.2 Woodland

Table 9 summarizes land acreages that NRCS identifies as having soil mapping units in the woodland land capability group. The NRCS soil mapping units land capabilities designations identify some mapping units as being suitable for sugar, pineapple, or woodland. These designations were assigned by NRCS when a hierarchical approach to land use was based on sugar and pineapple being more valued crops than wood. Thus land deemed suitable for sugar or pineapple was not always designated as appropriate for woodlands although nothing about the soils or slopes precluded wood production. In the current study, the approach to identifying mapping units for wood production was to include all soil mapping units that were identified as suitable for sugar, pineapple, or wood. Thus, the sugar soils identified in the previous section are included in the acreage shown in Table 9. Later analysis will address the hierarchical use of lands. The current section explores the ethanol potential from wood production on all soils deemed suitable for wood, including NRCS soils identified for sugar and pineapple.

Soil slopes in Table 9 are classified as 0 to 10%, 10 to 20%, and >20% and acreages in each group are presented by island. The data in Table 9 and the series of tables that follow are all arranged in the same manner and a description is provided here. The first data column in the table contains values for NRCS woodland soils (WS) that are zoned for agricultural use (NRCS-WS-ZA). The second and third data columns divide the acreage in the first column into categories according to annual rainfall. The second data column indicates the number of acres that have less than 20" and the third data column shows the acreage with greater than 20 inches (NRCS-SS-ZA>20"). Wood production is envisioned to be rainfed and land with less than 20" of annual rainfall is deemed unsuitable for this purpose. The fourth, fifth, and last data columns are each subsets of the third column based on land designation. The fourth column shows acreage of NRCS woodland soils that are zoned for agricultural use, have annual rainfall greater than 20", and are owned by the State of Hawaii (SOH). The fifth column shows acreage of NRCS woodland soils that are zoned for agricultural use, have annual rainfall greater than 20", and are owned by large land owners (LLO), including SOH. Agricultural lands of importance to the State of Hawaii (ALISH) that are zoned for agricultural use and have annual rainfall greater than 20" are presented in data column six.

Statewide there are almost 700,000 acres of NRCS-WS-ZA that have annual rainfall greater than 20" and 388,000 acres are on the island of Hawaii. This classification includes areas on Maui, Kauai, and Oahu in the range of 87,000 to 100,000 acres each. A comparison shows that more than 80% of the statewide total NRCS-WS-ZA land with annual rainfall greater than 20" is ALISH lands and 70% is in the hands of LLO. The SOH holds 160,000 acres. More than half of the acres included in any of the land designations are on the island of Hawaii.

Distribution of the woodland capability group on the major islands is shown in the maps labeled Figures 7 to 17. Colors on the maps indicate slope categories used in Table 9. Two maps of each island include areas suitable for *Leucaena* (annual rainfall 20 to 40") and *Eucalyptus* (annual rainfall >40").

Table 9. Acreages of NRCS woodland soils by land designation, slope, and rainfall.

	NRCS Woodland Soils					
	Total	Zoned Ag	Zoned Ag	Zoned Ag State Owned Lands	Zoned Ag Large Land Owners	Zoned Ag ALISH
Annual Rainfall	>0"	<20"	>20"	>20"	>20"	>20"
Island	acres	acres	acres	acres	acres	acres
Hawaii	553,814	45,494	388,492	114,112	277,125	330,742
0-10% slope	232,349	27,157	152,870	35,243	98,107	128,815
10-20% slope	302,822	18,337	218,156	77,109	169,318	186,220
20%+ slope	18,642	0	17,466	1,759	9,700	15,707
Maui	167,709	32,533	100,748	7,623	43,077	84,425
0-10% slope	60,546	26,325	24,157	832	19,666	22,626
10-20% slope	81,747	6,208	58,729	5,679	34,697	47,707
20%+ slope	25,416	0	17,862	1,112	16,004	14,093
Lanai	24,904	10,841	9,890	47	9,871	9,272
0-10% slope	21,283	9,446	8,993	47	8,976	8,459
10-20% slope	3,622	1,395	897	0	895	813
20%+ slope	0	0	0	0	0	0
Molokai	50,889	22,353	19,585	6,411	17,040	13,775
0-10% slope	34,515	18,296	10,188	3,797	8,916	8,138
10-20% slope	13,526	4,049	7,087	2,216	6,438	4,802
20%+ slope	2,849	7	2,309	397	1,686	835
Oahu	205,862	7,313	87,278	6,387	74,504	57,348
0-10% slope	108,467	6,481	50,286	3,420	42,374	43,033
10-20% slope	27,406	745	12,762	1,418	10,374	8,929
20%+ slope	69,988	87	24,231	1,549	21,756	5,386
Kauai	150,391	460	92,640	25,780	69,423	75,498
0-10% slope	74,785	460	54,603	15,154	40,860	49,398
10-20% slope	36,394	0	23,991	7,714	18,452	19,102
20%+ slope	39,212	0	14,046	2,912	10,111	6,998
State Total	1,153,570	118,993	698,632	160,360	491,040	571,060
0-10% slope	531,945	88,166	301,098	58,495	218,901	260,468
10-20% slope	465,517	30,733	321,621	94,136	240,173	267,573
20%+ slope	156,107	94	75,913	7,729	59,256	43,019

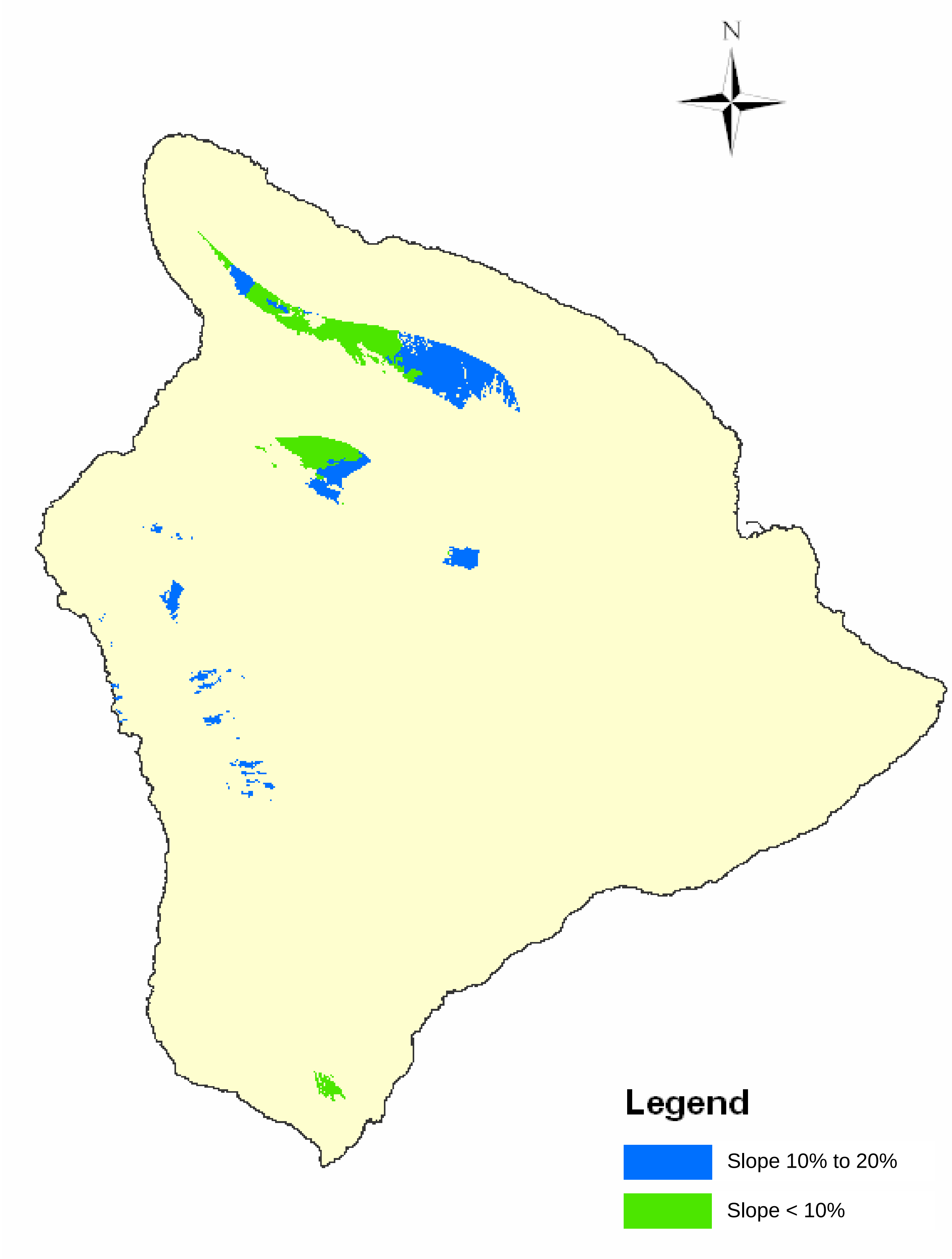

Figure 7. Map of NRCS *Leucaena* soils on the island of Hawaii showing slope classifications.

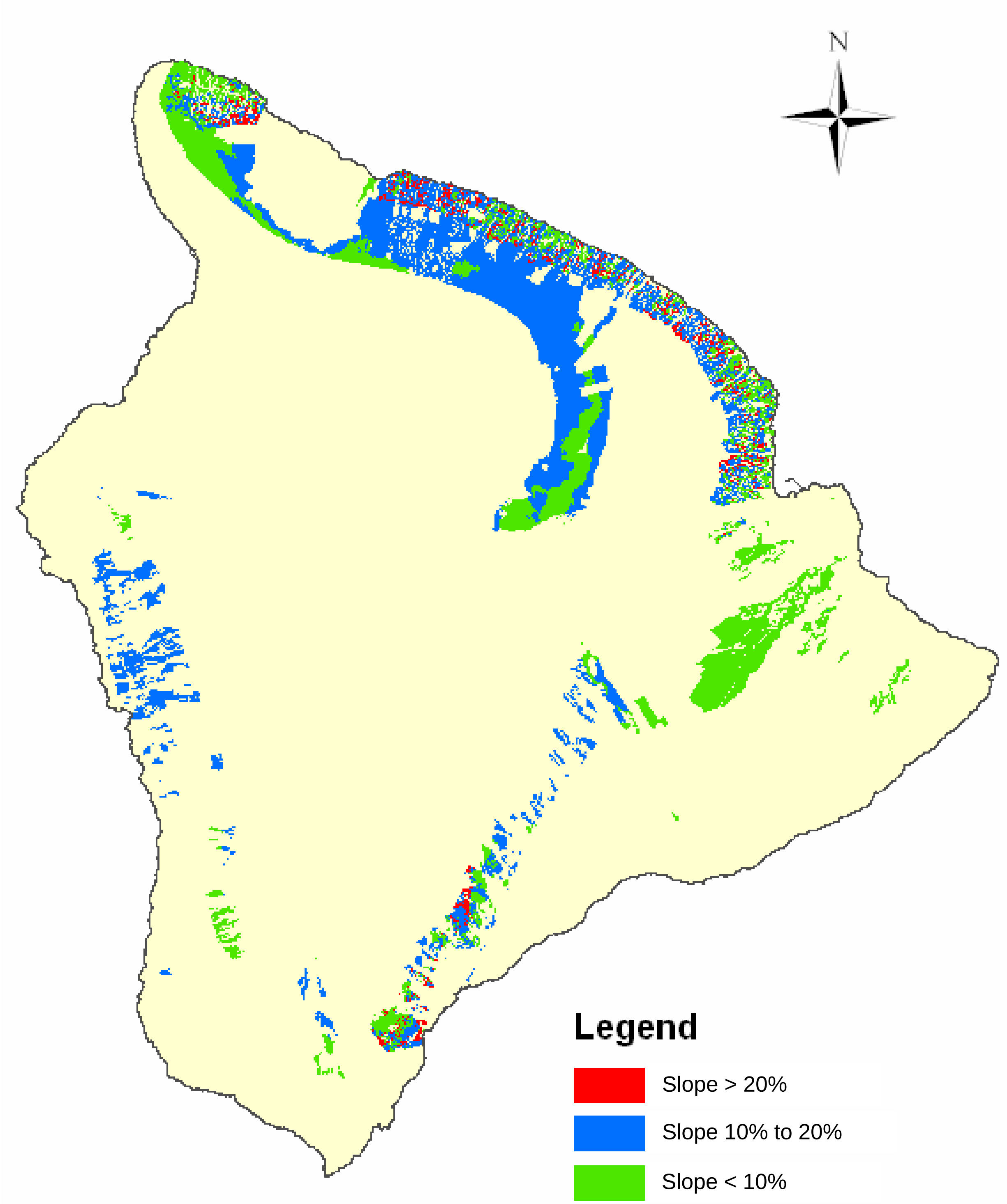

Figure 8. Map of NRCS *Eucalyptus* soils on the island of Hawaii showing slope classifications.

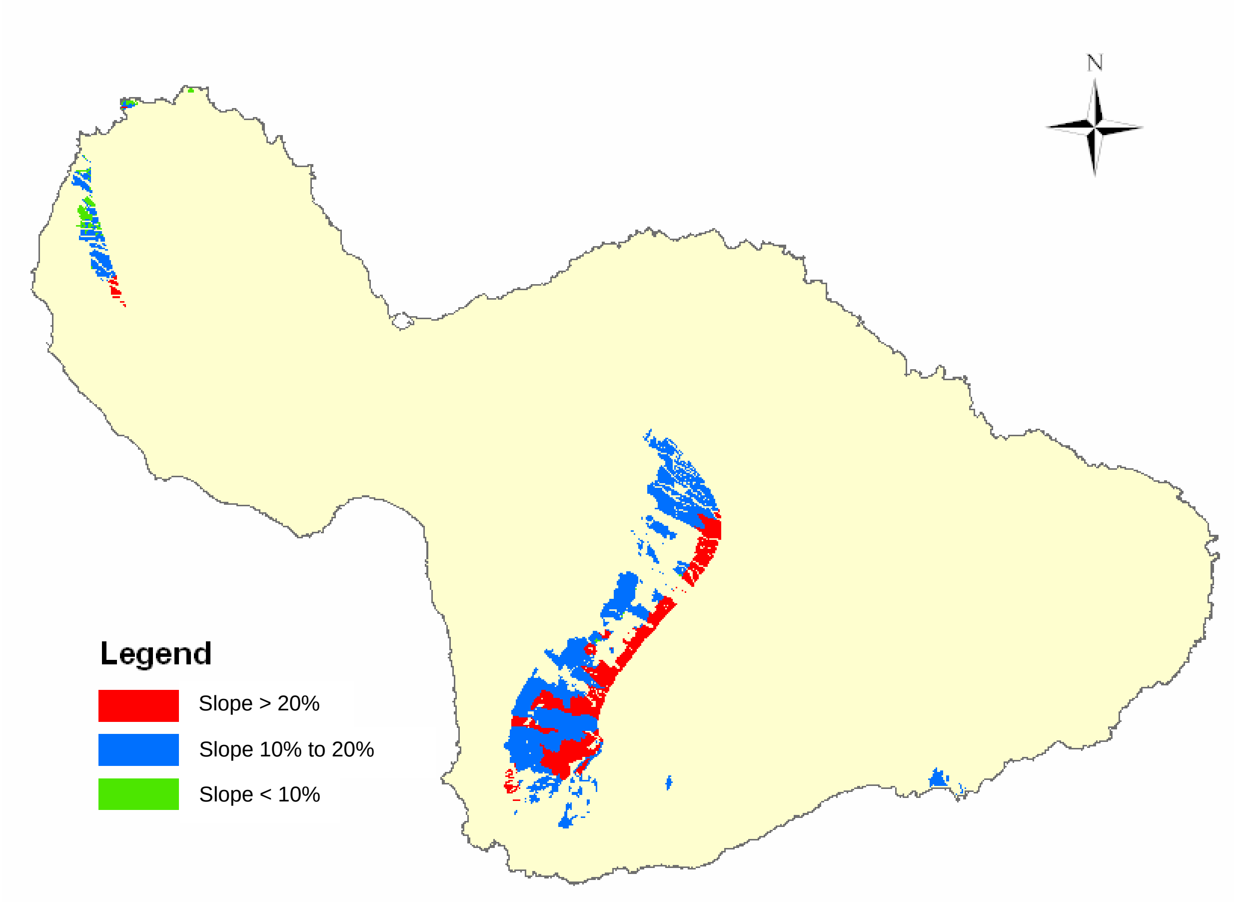

Figure 9. Map of NRCS *Leucaena* soils on the island of Maui showing slope classifications.

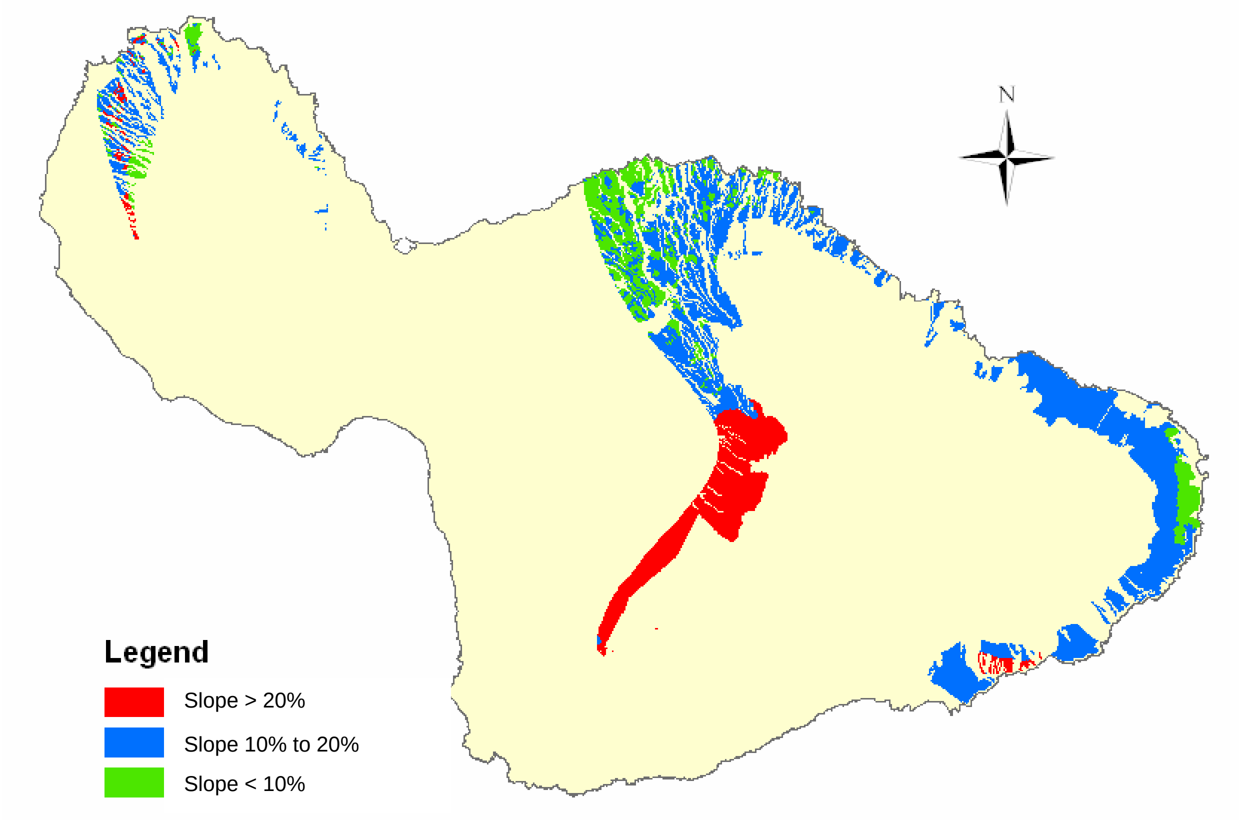

Figure 10. Map of NRCS *Eucalyptus* soils on the island of Maui showing slope classifications.

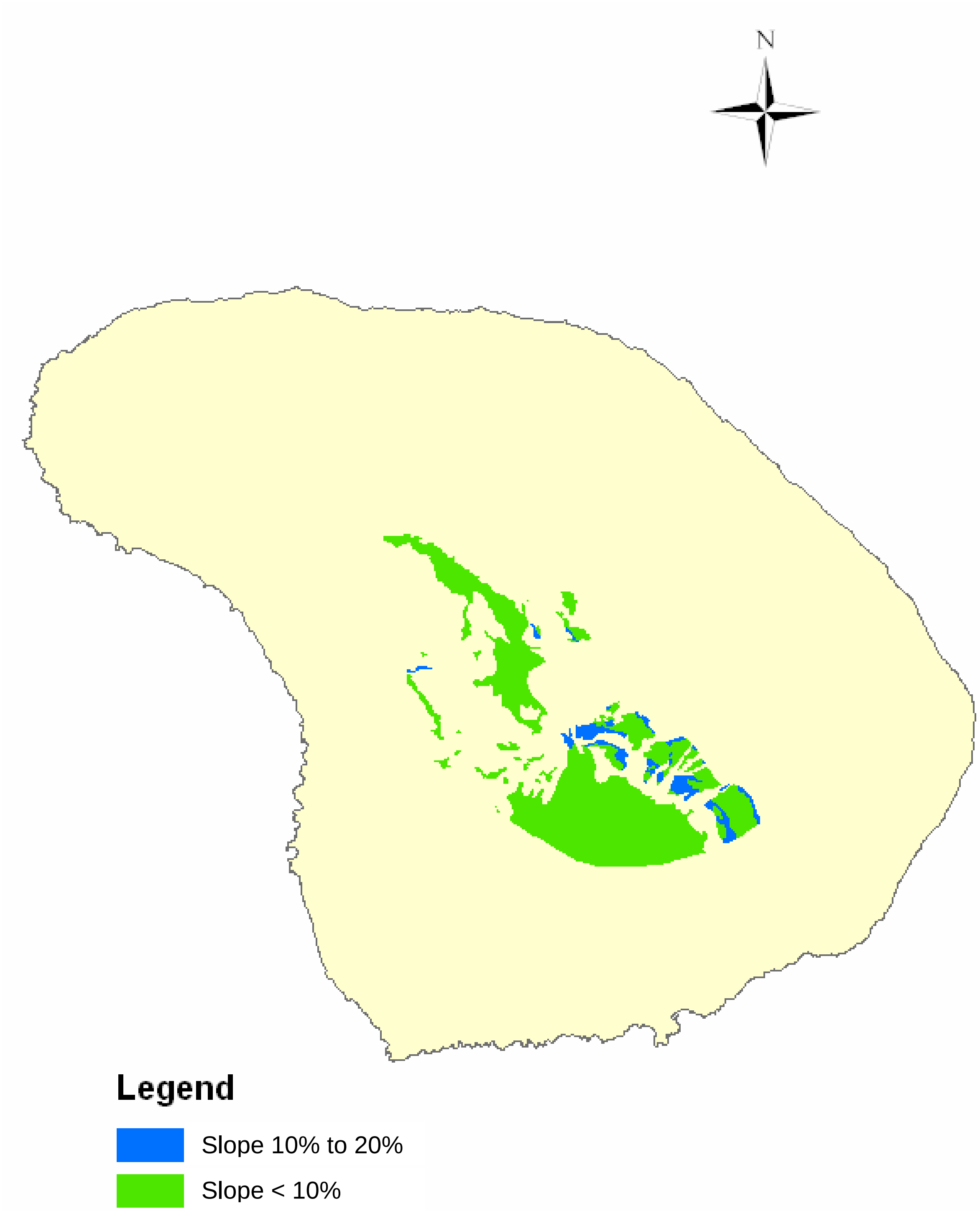

Figure 11. Map of NRCS *Leucaena* soils on the island of Lanai showing slope classifications.

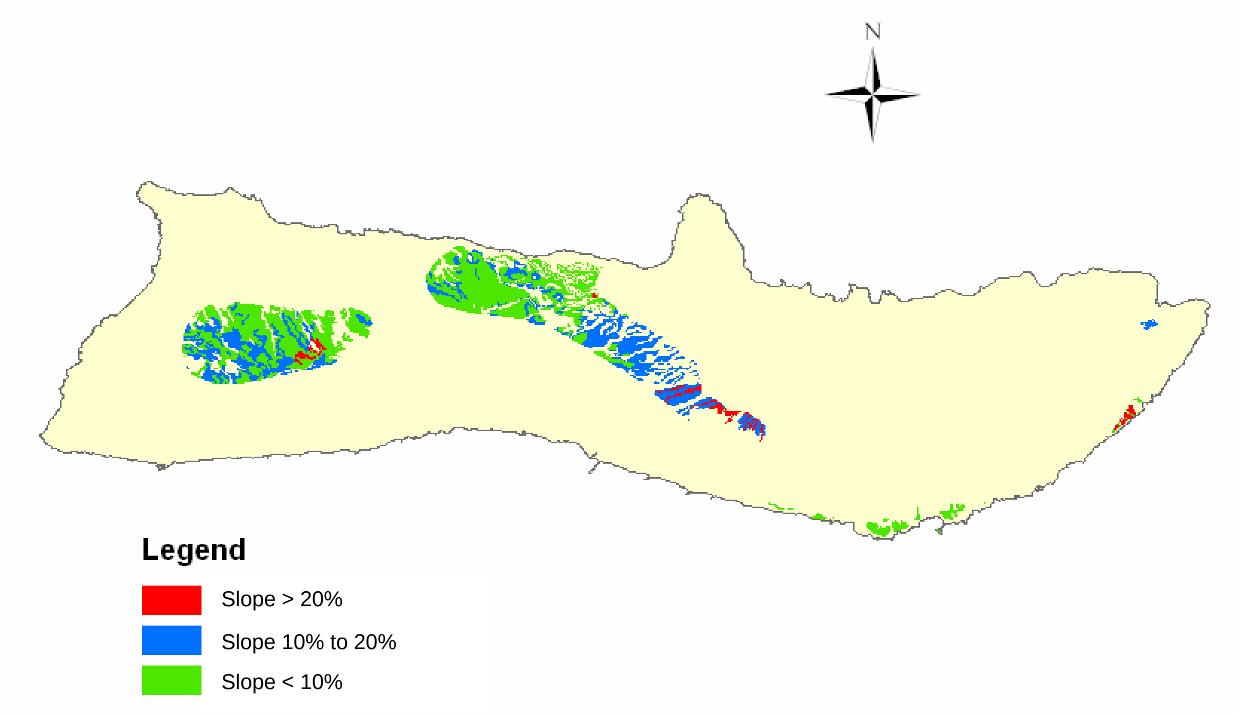

Figure 12. Map of NRCS *Leucaena* soils on the island of Molokai showing slope classifications.

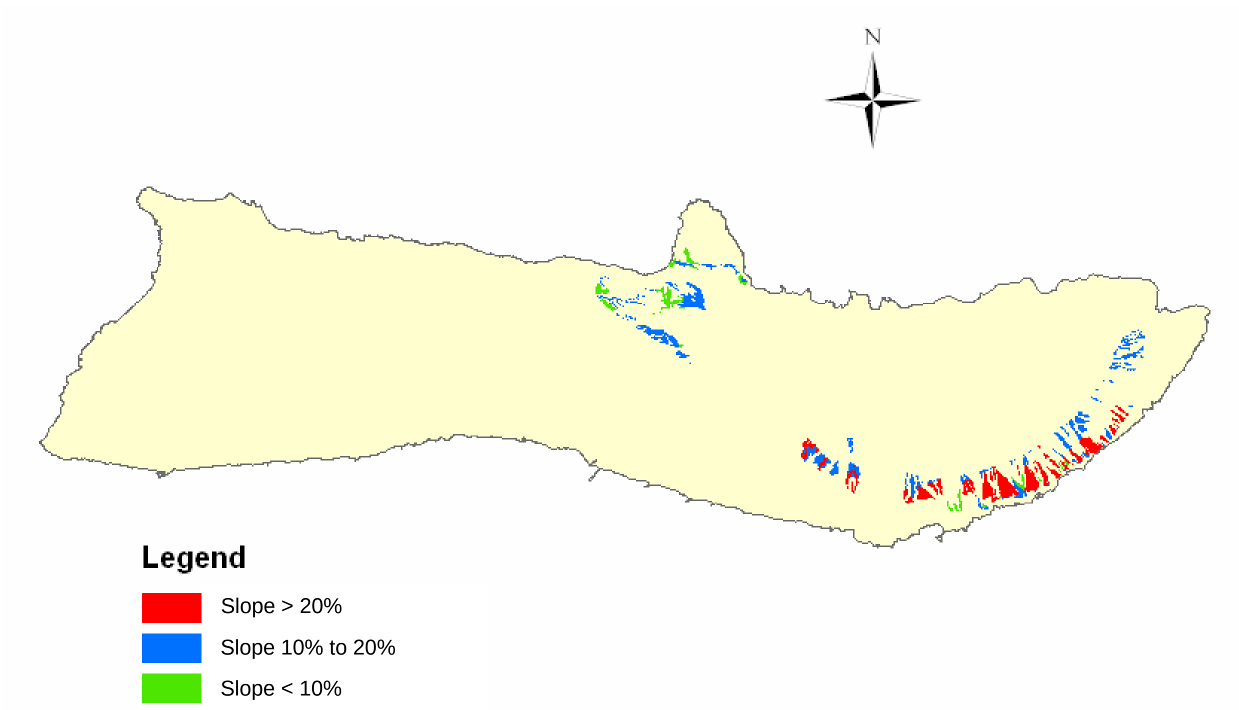

Figure 13. Map of NRCS *Eucalyptus* soils on the island of Molokai showing slope classifications.

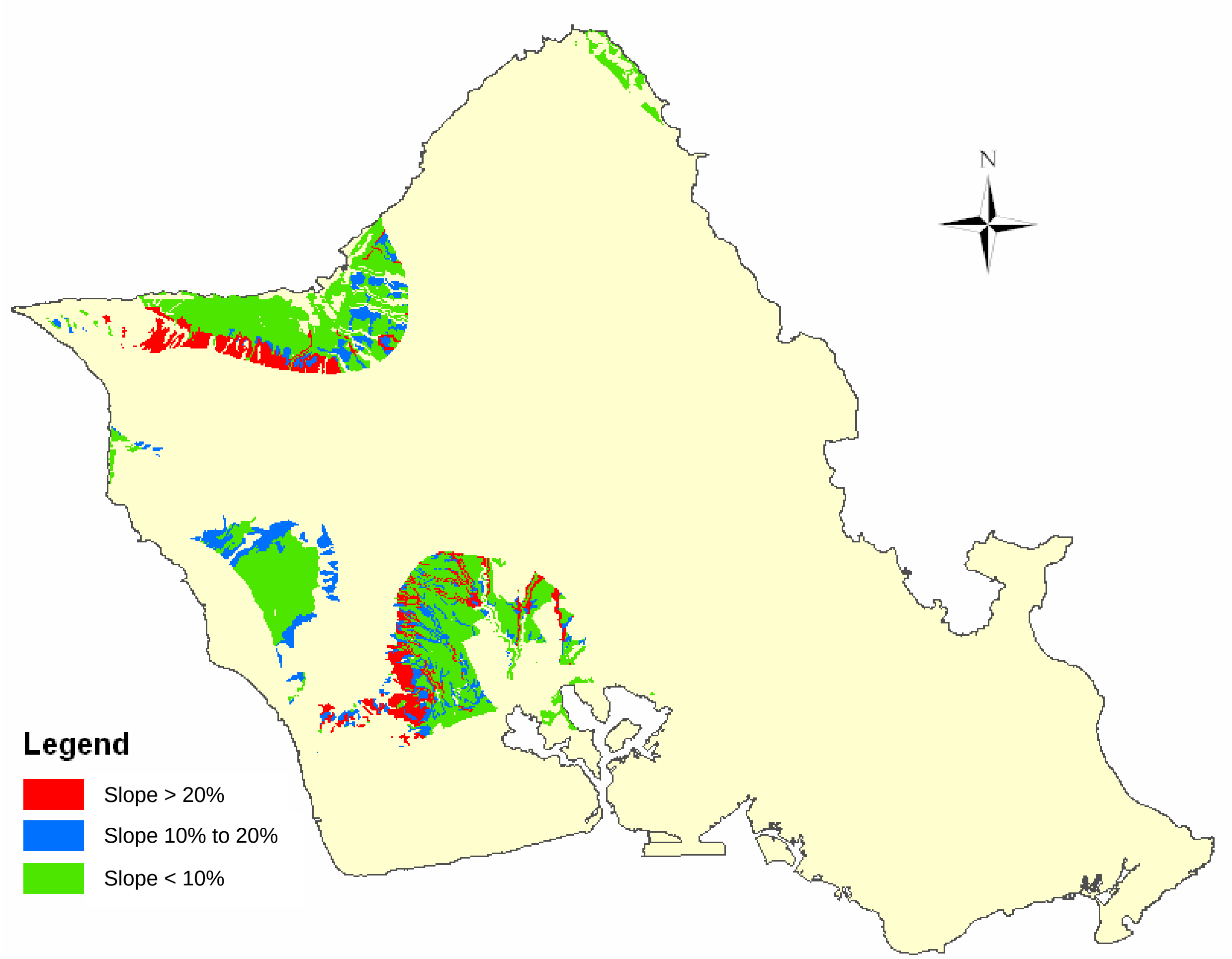

Figure 14. Map of NRCS *Leucaena* soils on the island of Oahu showing slope classifications.

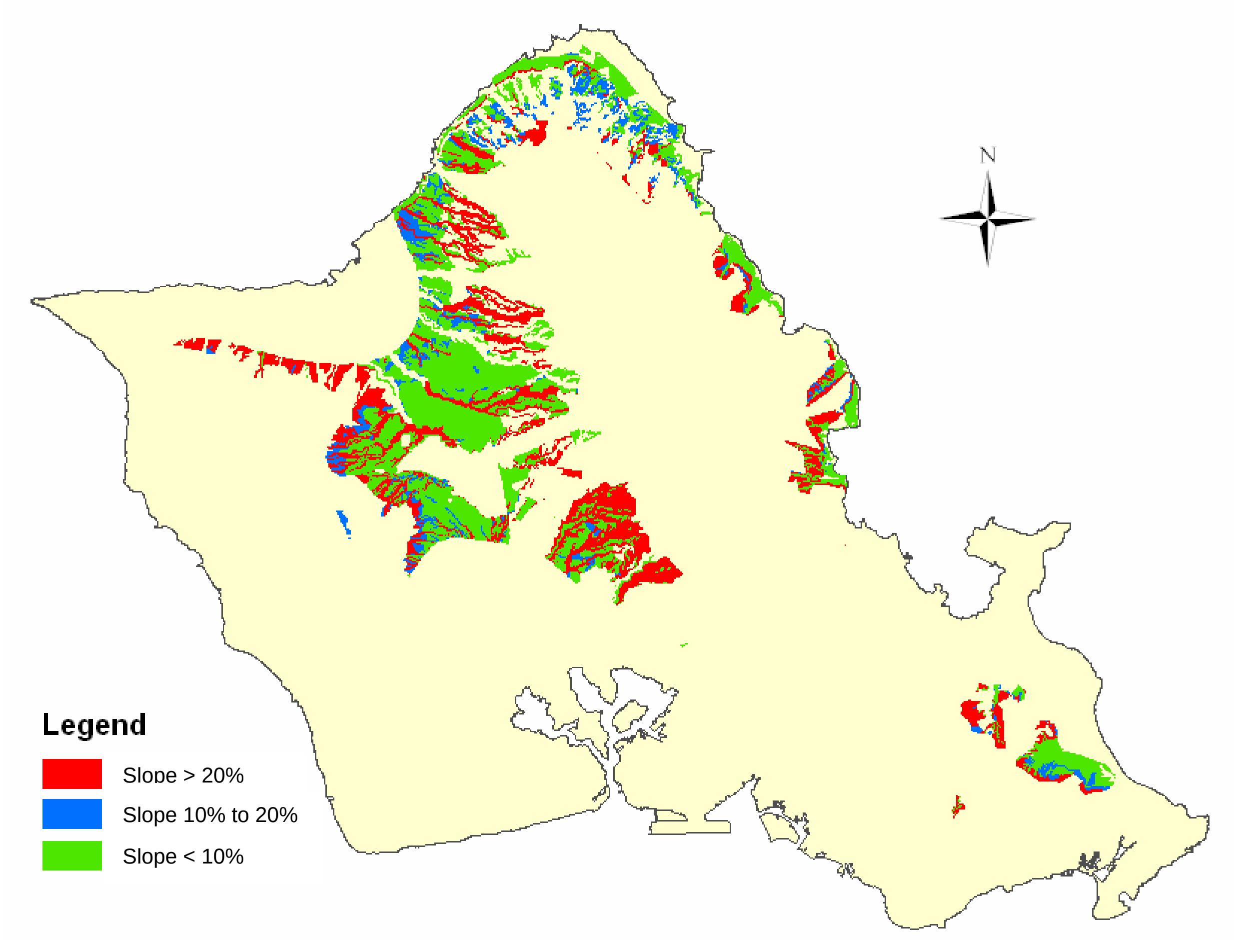

Figure 15. Map of NRCS *Eucalyptus* soils on the island of Oahu showing slope classifications.

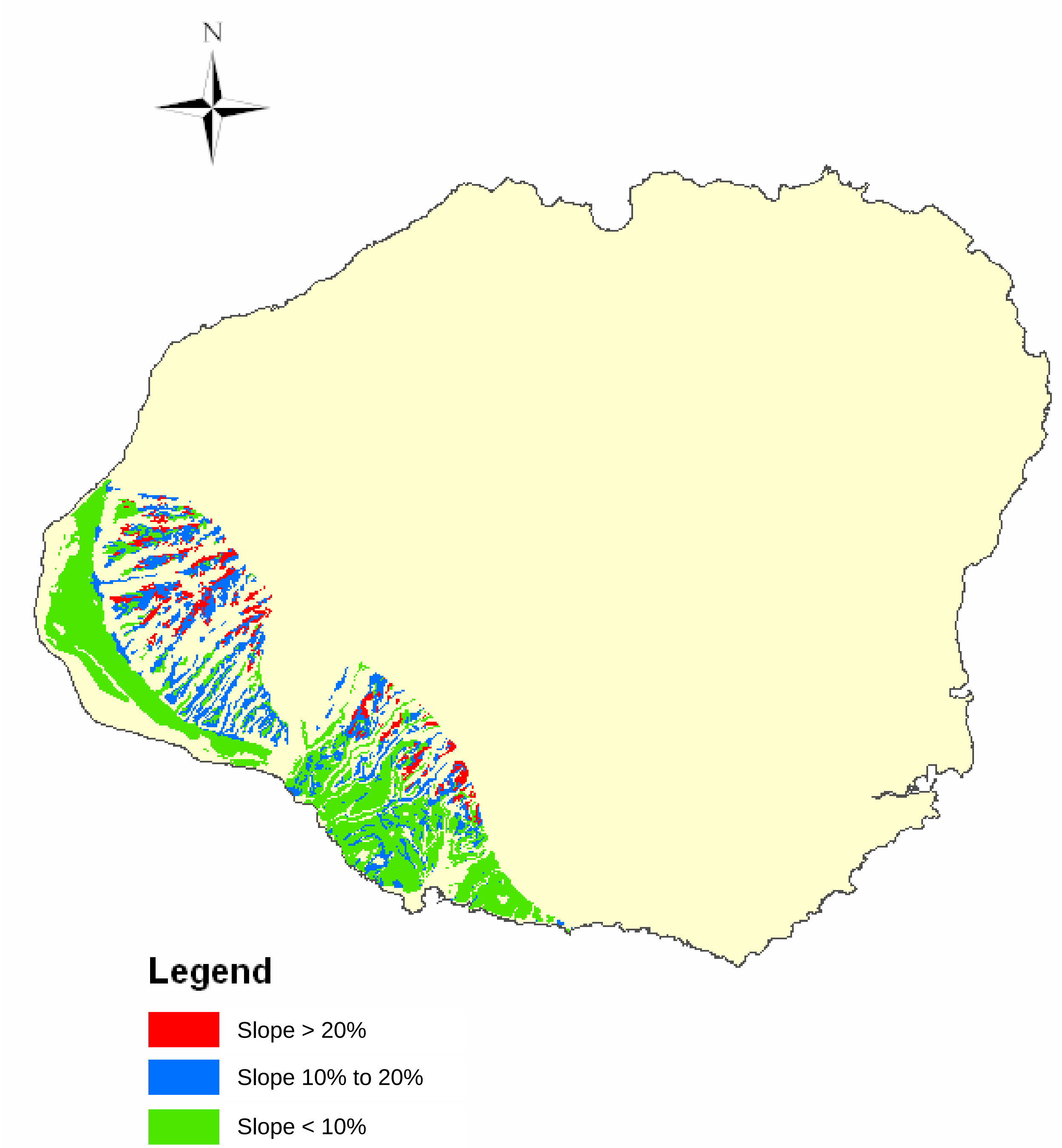

Figure 16. Map of NRCS *Leucaena* soils on the island of Kauai showing slope classifications.

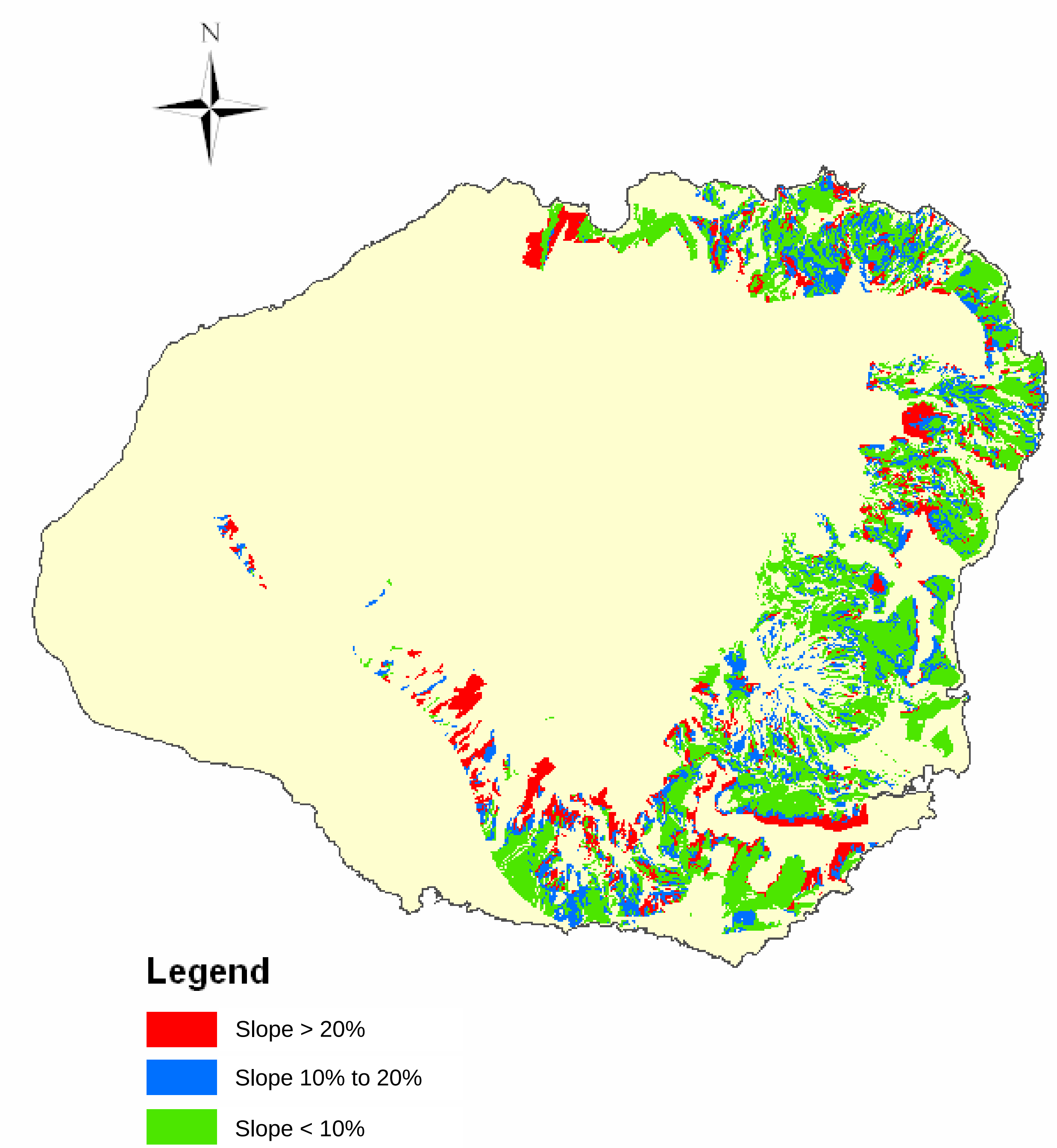

Figure 17. Map of NRCS *Eucalyptus* soils on the island of Kauai showing slope classifications.

7.2.1 Slope

43% of the 658,000 acres of statewide NRCS-WS-ZA with annual rainfall >20" have slopes of less than 10%, 46% have slopes between 10 and 20%, and the remainder, 11%, have slopes greater than 20%. These high slope soils are spread fairly evenly between the larger islands with each having in the range of 14,000 to 25,000 acres.

7.2.2 Rainfall

Silviculture in Hawaii has been conducted on lands where annual rainfall is sufficient to support tree growth. While many species have been considered for commercial forestry, two, *Leucaena leucocephala* and *Eucalyptus,* were chosen for this study based on their ability to be productive in lower (20" to 40") and higher (>40") rainfall areas, respectively. The land area data sets from Table 9 were further characterized according to their annual rainfall using the State of Hawaii GIS layer as shown in Table 10. Of the nearly 700,000 acres of NRCS-WS-ZA soils in the state, almost 70% could be used for *Eucalyptus* production according to this simple classification. *Eucalyptus* lands account for between 50 and 80% of the NRCS-WS-ZA lands on Hawaii, Maui, Oahu, and Kauai. Molokai and Lanai differ in that *Leucaena* accounts for more than 75% of the NRCS-WS-ZA lands. NRCS-WS-ZA SOH, LLO, and ALISH categories are split along similar percentages on all islands.

7.2.3 Ethanol Potential

Yields for *Leucaena* and *Eucalyptus* vary depending on location and cultural practices. A study that managed *Eucalyptus* as a short rotation woody crop on the island of Hawaii found yields of 11 tons per acre per year was possible for harvest ages of 5, 6, and 7 years [47]. Similar yields were recorded from giant *Leucaena* trials grown in Hawaii [26]. Based on these studies, yields of 10 tons of dry matter per acre per year were used in the present study to estimate wood production potential from *Leucaena* and *Eucalyptus* on the NRCS-WS-ZA lands.

Projections of ethanol and electricity production potential from plantation grown wood using lignocellulosic conversion technology are presented in Table 11 and 12. The volumes of ethanol that could be produced from wood on the larger acreages available as NRCS-WS-ZA lands are very similar to the totals predicted from sugar production on the NRCS-SS-ZA soils in the previous section. For example, the 428 million gal ethanol/yr potential (Table 8) from sugar cane grown on 360,000 acres (Table 2) statewide is very comparable to the 489 million gal ethanol/yr potential (Table 11) from short rotation woody crops grown on 698,000 acres (Table 9). Potential ethanol production volumes are also similar for LLO and ALISH land designations. Electricity production is roughly five times larger than that observed under the sugar cane scenario due to the greater acreage and higher fiber production rates for the wood species. Electricity was produced in the same proportion, 2.3 kWhr per gallon of ethanol from fiber, as that used for excess fiber in the sugar cane scenario.

Table 10. Potential leucaena (20" to 40") and eucalyptus (>40") acreages of agriculturally-zoned NRCS woodland soils by land designation.

	NRCS Woodland Soils							
	Zoned Ag	Zoned Ag	Zoned Ag State Lands	Zoned Ag State Lands	Zoned Ag Large Land Owners	Zoned Ag Large Land Owners	Zoned Ag ALISH	Zoned Ag ALISH
Annual Rainfall	20" to 40"	>40"	20" to 40"	>40"	20"to 40"	>40"	20" to 40"	>40"
Crop Island	Leucaena acres	Eucalyptus acres	Leucaena acres	Eucalyptus acres	Leucaena acres	Eucalyptus acres	Leucaena acres	Eucalyptus acres
Hawaii	76,335	312,156	26,655	87,457	70,217	206,908	68,868	261,874
Maui	47,041	53,708	3,918	3,705	36,467	6,610	42,739	41,686
Lanai	9,890	0	47	0	9,871	0	9,272	0
Molokai	15,485	4,100	5,788	623	14,012	3,028	11,765	2,010
Oahu	34,973	52,305	2,183	4,204	30,240	44,263	25,000	32,347
Kauai	28,598	64,042	15,924	9,856	27,551	41,872	23,281	52,218
State Total	212,322	486,310	54,514	105,845	188,359	302,680	180,925	390,135

Table 11. Potential ethanol production from lignocellulose from short rotation woody crops grown on agriculturally-zoned NRCS woodland soils by land designation.

	NRCS Woodland Soils Zoned Ag											
	Zoned Ag			Zoned Ag State Lands			Zoned Ag Large Land Owners			Zoned Ag ALISH		
Crop	Leuc.	Euc.	Total	Leuc.	Euc.	Total	Leuc.	Euc.	Total	Leuc.	Euc.	Total
Island	million gal/yr			million gal/yr			million gal/yr			million gal/yr		
Hawaii	53.4	218.5	271.9	18.7	61.2	79.9	49.2	144.8	194.0	48.2	183.3	231.5
Maui	32.9	37.6	70.5	2.7	2.6	5.3	25.5	4.6	30.2	29.9	29.2	59.1
Lanai	6.9	0.0	6.9	0.0	0.0	0.0	6.9	0.0	6.9	6.5	0.0	6.5
Molokai	10.8	2.9	13.7	4.1	0.4	4.5	9.8	2.1	11.9	8.2	1.4	9.6
Oahu	24.5	36.6	61.1	1.5	2.9	4.5	21.2	31.0	52.2	17.5	22.6	40.1
Kauai	20.0	44.8	64.8	11.1	6.9	18.0	19.3	29.3	48.6	16.3	36.6	52.8
State Total	148.6	340.4	489.0	38.2	74.1	112.3	131.9	211.9	343.7	126.6	273.1	399.7

Table 12. Potential ethanol and electricity co-production from short rotation woody crops on agriculturally zoned NRCS woodland soils by land designation.

	Zoned Ag		Zoned Ag, State Owned		Zoned Ag, Large Land Owners		Zoned Ag, ALISH		Actual Usage in 2005[1]	
Island	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	Gasoline million gal/yr as ethanol equivalent[2]	million kWhr/yr
Hawaii	271.9	625.5	79.9	183.7	194.0	446.2	231.5	532.5	112	1,116
Maui	70.5	162.2	5.3	12.3	30.2	69.4	59.1	135.9	94	1,188
Lanai	6.9	15.9	0.0	0.1	6.9	15.9	6.5	14.9		28
Molokai	13.7	31.5	4.5	10.3	11.9	27.4	9.6	22.2		36
Oahu	61.1	140.5	4.5	10.3	52.2	120.0	40.1	92.3	440	7,721
Kauai	64.8	149.1	18.0	41.5	48.6	111.8	52.8	121.6	42	449
State Total	489.0	1124.8	112.3	258.2	343.7	790.6	399.7	919.4	688	10,539

[1] Data from Hawaii Energy Data Book, http://www.hawaii.gov/dbedt/info/economic/databook/db2005/

[2] Gasoline sales by county converted to ethanol equivalent; 1 gal ethanol = 0.66 gal gasoline

7.3 Ethanol from Sugar Cane and Wood

The two previous scenarios considered either sugar or wood production on suitable soils according to NRCS classifications. The current scenario considers potential ethanol production based on giving first priority to sugar cane and planting the remaining acreage to short rotation woody crops, i.e. the total area to be planted would be the union of NRCS-SS-ZA and NRCS-WS-ZA lands with sugar planted on NRCS-SS-ZA lands and short rotation woody crops planted on the remainder. Estimated potential ethanol production under this scenario is summarized in Table 13. As expected, the combination resulted in greater ethanol production than either sugar or short rotation woody species as stand alone crops.

Statewide potential ethanol production on NRCS-ZA lands totaled 705 million gallon per year, exceeding 2005 sales of gasoline as ethanol equivalent of 688 million gallons. Under this scenario and for LLO and ALISH land designations, the counties of Hawaii, Maui, and Kauai could produce enough ethanol to exceed their 2005 demand. Byproduct electricity production would be 70 to 80% of the totals calculated for the wood production based scenario presented above.

Table 13. Potential ethanol and electricity co-production from agriculturally zoned NRCS sugar and woodland soils by land designation with first priority given to sugar cane and second priority given to short rotation woody crops.

Island	Zoned Ag		Zoned Ag, State Owned		Zoned Ag, Large Land Owners		Zoned Ag, ALISH		Actual Usage in 2005[1]	
	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	Gasoline million gal/yr as EtOH equivalent[2]	million kWhr/yr
Hawaii	313.5	479.6	84.3	167.3	217.0	375.5	270.5	398.2	112	1,116
Maui	130.3	160.8	8.7	12.5	82.5	70.9	117.4	134.7	94	1,188
Lanai	17.0	15.7	0.0	0.1	16.9	15.7	15.5	14.5		28
Molokai	33.9	32.2	11.4	9.3	30.6	28.0	26.9	23.0		36
Oahu	104.1	92.4	7.1	6.8	86.1	77.9	78.4	51.7	440	7,721
Kauai	105.8	80.1	30.6	22.3	80.3	60.5	90.2	59.5	42	449
State Total	704.6	860.8	142.1	218.3	513.5	628.4	599.0	681.6	688	10,539

[1] Data from Hawaii Energy Data Book, http://www.hawaii.gov/dbedt/info/economic/databook/db2005/

[2] Gasoline sales by county converted to ethanol equivalent; 1 gal EtOH = 0.66 gal gasoline

7.4 Banagrass

A fourth crop scenario was investigated – planting NRCS-SS-ZA lands in banagrass (*Pennisetum purpureum*) to produce fiber for subsequent conversion to ethanol. Yields of irrigated and unirrigated banagrass on soils suitable for sugar production are estimated to be 22 and 18 tons of dry fiber per acre per year, respectively [48]. Using these fiber production values and lignocellulose to ethanol conversion factors, ethanol and byproduct electricity production were estimated for the land areas designated in Table 4. Results are presented in Table 14.

This scenario results in potential production of 524 million gallons of ethanol per year on NRCS-SS-ZA lands. This is roughly 100 million and 35 million gallons per year greater than the annual ethanol production projected for the "all sugar" and "all wood" scenarios, respectively. The earlier scenario giving first priority to sugar cane with remaining acreage devoted to wood resulted in greater potential production, 705 million gallons per year. Although not considered here, a scenario of first priority to banagrass with remaining acreage devoted to wood could be expected to exceed this value. State totals for NRCS-SS-ZA SOH, LLO, and ALISH lands were 74, 374, and 480 million gallons per year, respectively. Note that under this scenario, SOH lands could be expected to provide more than 10% of the 668 million gallons of gasoline as ethanol equivalent consumed in 2005.

The banagrass fiber based scenario also develops the greatest amounts of co-product electricity for NRCS-SS-ZA lands and the LLO and ALISH land designations. Electricity production on Lanai and Molokai would be sufficient to meet 2005 sales, although this does not address increases in electricity use that may result from banagrass production.

Table 14. Potential ethanol and electricity co-production from banagrass on agriculturally zoned NRCS sugar soils by land designation.

Island	Zoned Ag		Zoned Ag, State Owned		Zoned Ag, Large Land Owners		Zoned Ag, ALISH		Actual Usage in 2005[1]	
	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	million gal/yr	million kWhr/yr	Gasoline million gal/yr as EtOH equivalent[2]	million kWhr/yr
Hawaii	181.8	418.1	20.2	46.4	91.3	210.0	168.2	386.8	112.3	1,116
Maui	91.0	209.4	4.9	11.3	77.8	179.0	88.6	203.9	93.9	1,188
Lanai	15.2	35.0	0.0	0.0	15.2	35.0	13.8	31.7		28
Molokai	30.0	68.9	11.2	25.7	27.7	63.8	25.5	58.5		36
Oahu	96.3	221.4	6.2	14.2	78.7	181.0	84.3	193.9	439.9	7,721
Kauai	110.3	253.7	32.1	73.7	83.5	192.1	99.8	229.5	41.9	449
State Total	524.5	1206.5	74.5	171.3	374.3	861.0	480.2	1104.4	688.1	10,539

[1] Data from Hawaii Energy Data Book, http://www.hawaii.gov/dbedt/info/economic/databook/db2005/

[2] Gasoline sales by county converted to ethanol equivalent; 1 gal EtOH = 0.66 gal gasoline

8. Production Costs

Ethanol production costs are primarily a function of feedstock cost. In the two largest ethanol producing countries in the world, Brazil and the United States, feedstock costs account for approximately 70% of the gross production cost for ethanol manufacture [49]. The most common feedstocks for ethanol are sugar cane molasses and juice, corn, and sugar beet molasses and juice. Fuel ethanol production has resulted in increased pricing pressure on all of these primary feedstocks. Molasses prices have seen extreme volatility over the last year with prices ranging from $50 to over $100 per ton.

In this study, near-term is defined as the time period through 2010. Given the status of development of the Hawaii ethanol industry and current production technology, the most likely indigenous feedstock for ethanol production in Hawaii in this time frame, is molasses produced at existing sugar factories. Midterm for the purposes of this study is defined as the period 2011 through 2015 and producing ethanol from sugar cane (juice/fermentable sugar based) could be in place in this time horizon. Should lignocellulosic ethanol (either biochemical or thermochemical) become commercial technology during the next nine years, it too could be employed. Certainly in the long term (2016 through 2025), biochemical and thermochemical lignocellulosic ethanol production are expected to be fully commercial and ready for deployment. Biorefineries may be based on a combination of sugar and lignocellulosic conversion technologies in order to achieve flexibility in the product mix, e.g., ethanol, sugar, power, etc. Although assessments of biochemical plants utilizing corn stover at a rate of 2,000 dry tonne per day (2,200 tons per day) have been conducted [23], analysis based on an integrated platform of sugar and lignocellulosic feedstocks with multiple products should be done for conditions representative of Hawaii.

The near-term (through 2010) scenario of using molasses to produce ethanol would be based on the roughly 80,000 tons of molasses annually produced in the state. This could yield 5.6 million gallons of ethanol based on a conversion rate of 70 gallons ethanol per ton molasses. Costs of production for ethanol from molasses in a 6 million gallon per year facility can be estimated as shown in Table 15. Feedstock costs are calculated directly from the molasses cost and ethanol yield. Estimated operating costs of $0.36 and $0.49 per gallon of ethanol produced from molasses are presented in the BBI [5] and USDA [42] reports, respectively. BBI also reports a capital cost of $0.23 per gallon of ethanol. The USDA report identifies capital costs of $41 million for a molasses based ethanol plant with capacity of 32 million gallon [42]. These data were used to scale capital costs for a 6 million gallon per year ethanol plant according to the equation

$$\left(\frac{C_1}{C_2}\right) = \left(\frac{Q_1}{Q_2}\right)^{0.6}$$

Where *C* is plant capital cost and *Q* is production volume. The scaling exponent of 0.6 is commonly used for chemical plant applications [50]. This calculation yields an estimated capital cost for a 6 million gallon per year plant of $15 million. Assuming zero equity in the project and $15 million amortized over a 20 year period with a 7% interest rate and annual payments, a simple calculation yields annual payments of $1.4 million. Dividing the annual payment by the annual capacity yields an estimate of capital costs of $0.23 per gallon, which agrees with the estimate from the BBI report. As shown in the table, total estimated cost of production for ethanol from molasses in a 6 million gallon per year plant ranges from $1.45 to $1.58 per gallon of ethanol.

Table 15. Estimated cost of production of ethanol from molasses for a 6 million gal per year plant.

Cost Item	Basis	$/gal EtOH
Feedstock	$60 per ton molasses 70 gal EtOH per ton molasses	0.86
Operating	BBI & USDA Report [7, 42]	0.36 to 0.49
Capital	BBI & USDA Report [7, 42]	0.23
Total[1]		1.45 to 1.58

[1] does not include tax credits or other government incentives

Cost effectiveness of producing ethanol in Hawaii can be assessed by comparing cost of production against prices of imported ethanol, recognizing that this does not internalize benefits that local production might accrue related to improved energy security, increased energy diversity, stimulation of the state economy, etc. Figure 18 shows an 18 month price history of gasoline blend stocks in Los Angeles including ethanol, alkylate (high octane component used in premium grades), and California reformulated gasoline blendstock for oxygenate blending (CARBOB) [51]. Note that the ethanol price is $0.51 per gallon lower than the actual cost, reflecting the inclusion of a federal tax credit, and Spot Alkylate Gulf includes a $0.20 per gallon transportation and distribution cost from the Gulf Coast. According to the figure, in the past 18 months, ethanol prices have ranged from $1.20 to $3.75 per gallon and removing the $0.51 per gallon tax credit would increase to $1.71 to $4.26 per gallon. Transportation costs from the west coast to Hawaii are estimated to add $0.29 per gallon [52]. This would increase the total cost of imported ethanol to $2.00 to $4.54 per gallon. It is prudent to note that sales of commodities such as fuel ethanol are often based on long term contracts rather than spot prices and these estimates are expected to be higher as a result. The cost of ethanol produced from molasses in Hawaii was estimated to range from $1.45 to $1.58 per gallon, suggesting that local production can compete against imports.

Another indicator of cost competitiveness is the comparison of the price of ethanol versus gasoline. Ethanol has 66% of the energy content of gasoline on a volumetric basis. Ethanol priced at $1.50 per gallon would be competitive with a wholesale gasoline price of $2.25 per gallon on an energy equivalent basis. The average retail price for regular unleaded gasoline blended with 10% ethanol in Hawaii on December 1, 2006, was $2.86 per gallon [53] and included taxes of $0.509 per gallon [54], yielding a pretax retail value of $2.35 per gallon. This value would necessarily include dealer profits and other charges, however it serves to show that ethanol produced for $1.50 per gallon could be competitively priced with gasoline on an energy equivalent basis.

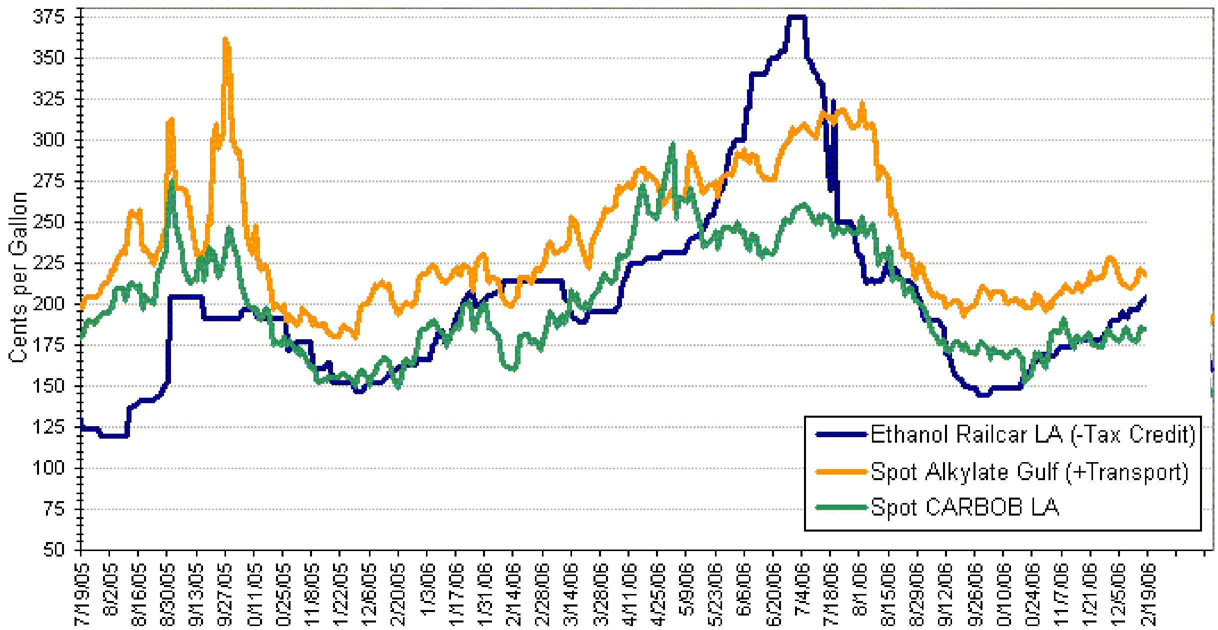

Figure 18. Eighteen month price history of California gasoline blend stocks in Los Angeles. Note that the ethanol price is shown after deducting a $0.51 per gallon federal tax credit and Spot Alkylate Gulf includes a $0.20 per gallon transportation and distribution cost from the Gulf Coast [51].

9. Summary and Conclusions

An assessment of biomass-based ethanol production potential was conducted for the State of Hawaii considering lands, crops, and conversion technologies. Evaluation of the spatial distribution of soil types, zoning, and annual rainfall, was conducted using geographic information system technology. The Natural Resources Conservation Service designation for soil types suitable for specific crops – sugar cane and wood species – was used as a first identifier of land suitability. These lands were reduced by restricting consideration to the subset zoned for agricultural use. Within the agriculturally zoned land in the state suitable for sugar and wood production, lands owned by the State of Hawaii, those owned by large land owners, and agricultural lands of importance to the state of Hawaii, were considered as sub-groups. Acreage for each is summarized in Table 16. Values range from 50,000 acres for NRCS sugar soils that are zoned for agriculture and owned by the State of Hawaii to nearly 700,000 acres for NRCS woodland soils that are zoned agricultural. Note that NRCS designations of soils suitable for sugar and wood are not mutually exclusive, i.e. some areas are suitable for either crop, and this is reflected in the acreages in the table.

Sugar cane, banagrass, *Leucaena,* and *Eucalyptus* were selected as potential ethanol feedstock crops based on historical crop production in Hawaii or extensive energy crop research trials and demonstrations conducted over the past 30 years. Sugar cane provides fermentable sugars and fiber, whereas the latter three crops are grown for fiber only. Crop water requirements were compared with annual rainfall for the selected land areas. It was assumed that sugar and banagrass would require 78 inches of irrigation annually, via rainfall or mechanical application; thus, lands receiving less than 78 inches of rainfall would need some applied irrigation to supplement rainfall. It was assumed that *Leucaena* and *Eucalyptus* would be grown without applied irrigation, that *Leucaena* was suitable for drier locations (20 to 40 inches), and that *Eucalyptus* was suitable for the areas receiving more than 40 inches of annual rainfall.

Historic production data for unirrigated (rainfed) and irrigated sugar cane in Hawaii were used to calculate average raw sugar yields of 4.2 and 6.4 tons per acre per year, respectively. Based on these values and molasses and fiber data, associated total fermentable sugar and fiber yields were calculated to be 4.6 and 7.1 tons per acre per year for unirrigated sugar cane and 7.0 and 10.9 tons per acre per year for irrigated sugar cane. Unirrigated banagrass and irrigated banagrass fiber yields were assumed to be 18 and 22 tons per acre per year, respectively. Fiber yields from *Leucaena* and *Eucalyptus* were estimated to be 10 tons per acre per year based on field trials and demonstration plantings.

Yields of ethanol from sugar and fiber were assumed to be 141 gallons per ton of fermentable sugars and 70 gallons per ton of fiber, respectively. These were used to calculate total potential statewide ethanol production as shown in Table 16. Four crop scenarios were investigated: 1) sugar cane grown on all soils suitable for sugar, 2) *Leucaena* and *Eucalyptus* grown on all soils suitable for trees, 3) sugar cane given first priority, grown on all soils suitable for sugar, and *Leucaena* and *Eucalyptus* given second priority, grown on remaining soils suitable for trees, and 4) banagrass grown on all soils suitable for sugar. The third crop scenario produced the most ethanol for each of the land subgroups with a maximum value slightly greater than 700 million gallons of ethanol per year. For comparison, the total motor gasoline sales in Hawaii in 2005 totaled 454 million gallons or 668 million gallons of ethanol on an energy equivalent basis. A renewable fuels target of 20% of motor gasoline, 134 million gallons of ethanol equivalent, could be produced under all crop scenarios with the exception of state owned lands under scenarios 1, 2, and 4.

Table 16. Summary table of statewide ethanol potential for four land groupings and four crop scenarios.

	Zoned Ag	Zoned Ag, State Owned	Zoned Ag, Large Land Owners	Zoned Ag, ALISH
1) Sugar cane				
Acres	360,324	50,828	252,145	329,520
Ethanol (mil gal/yr)	429	61	312	393
2) Trees				
Acres	698,632	160,360	491,040	571,060
Ethanol (mil gal/yr)	489	112	344	400
3) Sugar cane first priority, trees second priority				
Sugar Acres	360,324	50,828	252,145	329,520
Wood Acres	394,136	115,488	288,105	294,564
Ethanol (mil gal/yr)	705	142	513	599
4) Banagrass				
Acres	360,324	50,828	252,145	329,520
Ethanol (mil gal/yr)	525	74	374	480

The crop scenarios of the summary table do not reflect near-term potential ethanol production. For the purposes of this study, 2010 production of ethanol from molasses from existing sugar factories using readily available conversion technology was considered near term. Production costs were estimated to be $1.45 to $1.58. Comparison of estimated ethanol import costs based on west coast spot market prices and shipping costs ranged from $2.00 to $4.54 per gallon landed in Hawaii excluding incentives, suggesting that ethanol produced from local feedstock could be cost competitive. Similarly, $1.50 per gallon ethanol from molasses would translate to $2.25 per gallon of gasoline on an energy equivalent basis. Average retail gasoline prices without taxes were $2.35 per gallon on December 1, 2006, indicating that ethanol could be cost competitive with gasoline under favorable market conditions.

The scope of this report was to explore the potential for producing ethanol in Hawaii from indigenous feedstocks. This has been accomplished at a level that does not address many of the implementation issues that will be critical to such an endeavor; water availability and cost, land availability, land use priorities, impacts on environmental quality, economic impacts, and costs of production for ethanol conversion technologies that are currently in the development stage. Each of these merits additional study whether for guiding future government policy making or investing in ethanol production ventures.

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