Biodiesel Crop Implementation in Hawaii

By

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M. Poteet
Sept. 2006

Summary

The report contains information regarding the potential for future biodiesel production in the State of Hawaii. Hawaii is more dependent on imported petroleum than any other State in the Union. Because of the isolation and lack of resources, Hawaii is seeking opportunities to reduce its dependence on imported fuels. The development of biodiesel and its by- and co-products on a large scale as a source of transportation fuel and energy generation is an important step in this process.

The report contains information on potential locations for future biodiesel crop production, oilseed bearing crops that may potentially be used to extract the necessary oils for the transesterification process into biodiesel, and by- and co-products that may be derived from the production and processing of such crops into biodiesel. Tables 2 and 3 on pages 54 and 55 provide reported oil production of selected crops. In addition, general information is given on the infrastructure that may be required to implement production of biodiesel crops in Hawaii. Because such information can vary widely from crop-to-crop and location-to-location, a framework of factors to consider is given, but the specifics for such operations would best be addressed by an agricultural economist. Agricultural engineers would also be beneficial for future analyses regarding necessary equipment, processing facilities, and costs.

This report gives three scenarios for biodiesel production. Currently, there is no information available on crop oil production specific to Hawaii, or on the identification of an agriculturally suitable production scheme. These two facts suggest that the possible scenarios for production could be discussed in terms of methods of supplying such fuels. Three means of producing, processing and distributing biodiesel and its by- and/or co-products are presented. Policy development and the willingness and interaction amongst government officials, scientists, producers, landowners, and the people of Hawaii will ultimately determine whether the establishment of a biodiesel production system will occur in Hawaii.

The report concludes by isolating each island's capacity and potential for production. Information presented within the report is used to extrapolate possible yields and final products for each island. Individual crops and combinations of crops are recommended for each island's delineated location(s). The capacity of each island is an approximation operating under the assumptions that best management and agronomic practices will be in place. Assumptions on yields are made using data from outside sources. The availability of local field production data for the crops with the most potential is far too limiting at this time to provide an economic analysis of the suggested scenarios. Field trials with germplasm specifically selected to suit the delineated locations to begin gathering that data is the next step.

Because the development of crops for biodiesel production is a relatively new concept it does not necessarily mean that it is a process that should be delayed. By encouraging new research into crop identification, a commitment to a diversity of renewable fuels and reducing greenhouse gas emissions can be initiated. Focused efforts on the development of crops, processes and any distribution that will be associated with the adoption of biodiesel from plant materials will increase the likelihood of success.

This report is a first step in developing the necessary oil crop information to help in the decision-making process to balance the need to reduce the state's dependency on imported energy and its dependency on imported foods while continuing to support production of high value exportable crops within the constraints of Hawaii's limited land base.

List of Acronyms

ASTM - American Society for Testing and Materials

BMP - Best management practice(s)

BTU - British thermal unit (3,412 BTU's = 1 kw/h)

DBEDT - Department of Business, Economic Development and Tourism, State of Hawaii

EPA - United States Environmental Protection Agency

FAME - Fatty-acid methyl-ester (raw form of biodiesel)

HDOA - Hawaii Department of Agriculture

LUD - Land Use District (set by State Land Use Commission-State of Hawaii)

MPOB – Malaysian Palm Oil Board

NREL - National Renewable Energy Laboratory, Golden, CO, a division of U.S. Dept. of Energy

QA - Quality assurance

R&D - Research and development

UH - University of Hawaii

UN-FAO – United Nations Food & Agriculture Organization

USDA - United States Department of Agriculture

WVO - Waste vegetable oil

1. Purpose

1.1 Background information

Hawaii relies on imported petroleum for approximately 88% of its energy requirements for current demands from the generation of electricity, ground, marine, and air transportation, and other industrial uses. Electricity production accounts for 32% of the petroleum used, ground and marine transportation for 27%, air transportation for 34%, and other industry for 7%. The reliance on imported petroleum has developed due to Hawaii's lack of any petroleum reserves within or surrounding the island chain. Hawaii's isolated location in the Pacific Ocean, where it rests approximately 2,400 miles from the nearest continental landmass, has created a situation that not only increases the cost of petroleum products due to import costs, but also accentuates its reliance on insecure foreign sources of oil products. As oil demand increases around the globe, the competition for scarce resources increases, driving up prices associated with those products. Along with increased demand, the relative instability of many of the oil-producing nations in the Middle East has also fed the surge in prices of petroleum products that has taken place in recent years.

According to the Hawaii Department of Business, Economic Development, and Tourism (DBEDT), in 2001 petroleum consumption was 32.8 barrels on a per capita basis, with 19 barrels solely for transportation purposes. The transportation industry accounted for 34% of the consumption of energy by end-use sector, the highest of any sector, including electric power generation, industrial uses, and residential and commercial demands. During 2004, over 1 billion gallons of fuel were sold in the State of Hawaii, of which 43% was in the form of gasoline and 25% in the form of diesel fuel (DBEDT, 2005). Excluding aviation fuel usage, diesel accounted for 36% of the total fuel sold during that period. Highway usage of diesel fuel for 2004 was greater than 43 million gallons (163 million liters), and non-highway usage (electricity production, agriculture, construction, manufacturing, and aviation) was more than 220 million gallons (833 million liters). In late June 2006, the average price of diesel fuel for the State of Hawaii was $3.52/gallon, up over 25% from one year previous (DBEDT, 2006). The increasing costs of diesel fuel to industry in Hawaii could become of major economic consequence in coming years. This report aims to present viable alternative sources for biodiesel production to reduce reliance on imported petroleum-based diesel products.

Biodiesel is a renewable fuel derived from naturally occurring oils found in plants, such as soybean or safflower, or animal fats that undergo a transesterification process in order to be used in combustion-ignition (diesel) engines. Biodiesel is produced by reacting vegetable oils or animal fats with an alcohol (typically methanol) to yield a fuel that can be used in any combination with petroleum-based fuels in standard diesel engines. In order to be used in diesel engines, a biodiesel blend must meet the specifications for ASTM D 6751, a registration requirement of the EPA. Biodiesel burns cleaner than ordinary diesel fuel due to drastically reduced amounts of sulfur found in the biodiesel. Biodiesel, when manufactured from plant oils, is also considered to be in net carbon balance, since it only emits as much carbon dioxide as was initially sequestered, or stored, within the plant used for fuel production.

The largest consumer of biodiesel is the United States Navy, whose prevalence in Hawaii would make for a substantial market to be further tapped. Biodiesel production reached nearly 25 million gallons in the US in 2004, and production facilities were either in operation or being planned in 36 states, including Hawaii, as of September 2005 according to the National Biodiesel Board (NBB, 2005). Hawaii currently has one production facility in operation on Maui, with one in the planning stages for Oahu. The plant on Maui, owned and operated by Pacific Biodiesel, currently recycles used vegetable oils from restaurants to produce its biodiesel. The establishment of biodiesel crops would significantly increase the volume of biodiesel that could be produced in Hawaii.

To assist in achieving the energy-independence goals set forth by the State of Hawaii for the year 2020, the Hawaii Department of Agriculture (HDOA) has requested this report on the feasibility of biodiesel crop production on the islands. The use of recycled vegetable oils as a biodiesel source is limited. The objective of this report is to identify potential crops for biodiesel production in Hawaii, crop production scenarios and combinations of potential sites and crops on the various islands. The findings can be used to help guide the resource allocation, infrastructure development, production methods, and marketing requirements associated with incorporating biodiesel crop production into an alternative fuels economy for the State of Hawaii.

Due to the variable conditions across the State in regards to land and resources available, three different production scenarios are described. Because of uncertainty in interisland transportation for biofuels the dependence on imported oil products is considered on an *island-to-island* basis. The three scenarios for production can be implemented independently or in conjunction with one another on any island. This report is intended to provide a starting point for the considerable information needed to make decisions regarding an oil crop industry. Considering the lack of production information available in Hawaii the suggestions in this report are not meant to be interpreted as coming from experts in the production of these crops. However, based on extensive experience in local agriculture in Hawaii's multi-environmental niches and the reported characteristics of oil crops throughout the world this report is attempting to provide a reasoned starting point for the development of a biodiesel industry.

It is not the intent of this report to suggest replacement of existing crop production already occurring on good agricultural lands with oil crops, but rather to point out the potential of selected acreage for oil crop production.

1.2 Methodology

This report was prepared after conducting exhaustive background research into potentially available oilseed-bearing or oil-containing crops and trees from around the world. From a comprehensive list of potential sources of extractable vegetable oils that could be transesterified into fatty-acid methyl ester (FAME), or biodiesel, the crops and trees with the greatest likelihood for implementation were included in this report. Efforts were made to identify important characteristics for each potential crop in order to evaluate any possibility for sustainable production in Hawaii. Where possible, any information about past commercial or scientific production of the isolated species was gathered and included.

Upon identifying crops for further analysis, a brief summary outlining specific data about those plants being grown for biodiesel production around the world was written. Attempts made at estimating potential production in Hawaii, even though there is little published information available for oil crops that have been grown in the Islands. This lack of information creates the major shortcoming of this report that cannot be addressed simply owing to the lack of past production in Hawaii.

After discussion of potential crops and trees to be grown for biodiesel production, suitable areas on each island were identified as possible locations for future large-scale production. This was a relatively arbitrary part of the report, as land is only as available as the owners are willing to allow its use. Areas have been isolated based on past land use, infrastructure in place or easily accessed, soil quality, climatic factors, and State Land Use Commission LUD's (land use districts).

For any biodiesel crop to be successful it will require the development of markets for by- and co-products from the transesterification process and the leftover materials from oil extraction. Markets for these products will need to supplement the biodiesel market for the oil crop chosen for production. Because of a relative lack of data and economic experience, the By- and Co-product Market Development section of the report serves as a summary of potential products that could be utilized from one or more of the crops and trees isolated for analysis. The concept of supplemental by- and co-product utilization will be best approached by a collection of experts involved with crop production and processing. Experts in development of alternative uses for plants and their by-products should be consulted for the identification and development of new and unrecognized compounds that may be available on a large scale once widespread implementation of biodiesel crop production has been undertaken.

The utilization of currently-in-place and development of new infrastructure are also considered within this report. It is expected that any significant production of oilseed crops for biodiesel production would take place on lands that have a history of agricultural production, thus any need for access to these areas would be easily met by pre-existing farm access roads. Transporting finished products to centralized processing and distribution facilities whether from the selected areas in this report or others not reported on can occur using the existing state's highway system. The installation of processing facilities, storage equipment, and supply centers will be the most costly part of any biodiesel implementation strategy. These issues are addressed specifically within Section 6 presenting scenarios for biodiesel production throughout the State.

One objective of this report is to provide three scenarios for production of biodiesel crops in Hawaii. The three production approaches described are plantation-style production, small, organized co-operatives, and individual production for on-farm utilization. Within each approach, methods for developing the necessary markets and infrastructure would be different, so this report aims to give as much insight as possible into the challenges to be faced by producers and users of biodiesel from oilseed crops grown under each scenario.

Section 7 isolates each island and its potential for biodiesel crop production. This portion of the report provides one or more options for all seven of the populated islands of Hawaii. The data in Section 7 is conjecture based on worldwide yields and potentials that have been realized internationally. The extrapolation of data to Hawaii assumes that with the climate in place, the access to fully mechanized operations, the necessary research tools available, and sufficient investment opportunities for local and outside entities, Hawaii would be able to produce efficient, high-yielding biodiesel crops to assist in the long-term goal to reduce imports of petroleum-based fuels.

The focus of this report is to provide information to HDOA on potential crops that may be grown locally to supply Hawaii's demand for the biofuel, biodiesel. Many crops are grown around the world to supply the world with its necessary vegetable oils. In the past, these vegetable oils have been used mostly for food, lubrication, protective coverings, and fuel. This report has identified crops and trees that may be able to supplement Hawaii's transportation, industrial, agricultural, and energy sectors with sustainable, clean-burning biofuels. From the findings in this report, it is expected that HDOA would have some basic information to assist local producers and landowners wishing to supply Hawaii with significant amounts of biodiesel. Much work remains to be done with many of the potentially viable crops presented herein. This report will help to establish guidelines to develop the information needed to determine which of the various oil crops would support the State of Hawaii's efforts to be less dependent on outside energy sources.

2. Available Land for Production

The primary factor for consideration in the development of any biodiesel crops in Hawaii is the availability of the land necessary to produce such products. Not only will large areas of land be necessary for production, but the site suitability and potential agronomic productivity of the land must be determined. These issues will dictate which areas of the State may be utilized for future production. One objective of this study is to determine suitable locations in the Islands that can efficiently produce biodiesel crops while still being conveniently accessible to major consumers of diesel fuel, including agricultural, industrial, and population centers, that will require the fuel once it is produced.

Because of the unusual nature of Hawaii's geography, an island-by-island approach to biodiesel crop production will be the most logical. Each island has unique growing conditions, including soil types, climatic factors, available land, and infrastructure currently in place. It is possible that excess biodiesel produced on neighbor islands could supplement Oahu's needs, but costs of shipping might make this option less desirable by producers and suppliers of the biodiesel. The consumption of diesel fuels is greatest in the City and County of Honolulu, with total consumption in 2004 of almost 183 million gallons (693 million liters). The counties of Maui, Hawaii, and Kauai accounted for the other 80 million gallons (302 million liters) consumed in 2004 (DBEDT, 2005). It is expected that the biodiesel necessary to meet the needs of the neighbor islands will be produced on those islands. Biodiesel production for Oahu will be a greater challenge, as producing enough B-20 to meet the island's needs would require nearly 37 million gallons of biodiesel, based on 2004 figures. With consumption likely to increase in coming years, this total will be even larger.

This section will focus on lands designated for 'Agricultural' use by the State of Hawaii's State Land Use Commission. Lands currently designated as 'Conservation' may also be considered in the future by the State for production of oil crops grown on trees. Production in 'Conservation' districts could require substantial investment if not previously farmed. Because the nature of this report is to identify agricultural commodities to be grown on agricultural lands, only land classified as 'Agricultural' will be considered for each Island. As of December 2004, there were 1,931,378 acres (781,934 hectares) of land classified as 'Agricultural' by the State Land Use Commission (DBEDT, 2005).

The report for each island was to identify potential lands on the islands that may be utilized for biodiesel production. Every attempt has been made to locate lands nearby or adjacent to major thoroughfares. The ability to harvest crops, get them to processing facilities and delivered to distribution points will be one of the important factors when crop production for biodiesel has begun. The crops that will be recommended for each island will be addressed in Section 7. The identification of various locations serves to provide flexibility in determining where the focus of biodiesel production on each island might take place. The use of private lands is obviously up to the landowners themselves. The inventory herein identifies the principle players holding land that could be used to facilitate future development of a biodiesel-from-cropping source to complement the existing biodiesel-from-waste vegetable oil (WVO) source.

Primary constraints for biodiesel production on each island will include land and water availability and the lack of a community of growers with knowledge of the production schemes that must be implemented to successfully produce oilseed crops. The increasing competition for water across Hawaii will drive up costs of production for any agricultural operation, so utilization of marginal lands and crops with low water requirements should be taken into consideration. Land costs in the islands are so excessive that it may be very difficult for any large-scale operation to begin producing biofuels in sufficient quantity to meet the island's demand. A lack of experienced, independent farmers who own their own parcels of land may make production of large areas of a low-valued or commodity crop more difficult than similar operations located on the mainland. These factors must be considered in any long-term decision made on implementing biodiesel crop production, especially on Oahu.

2.1 Island of Oahu

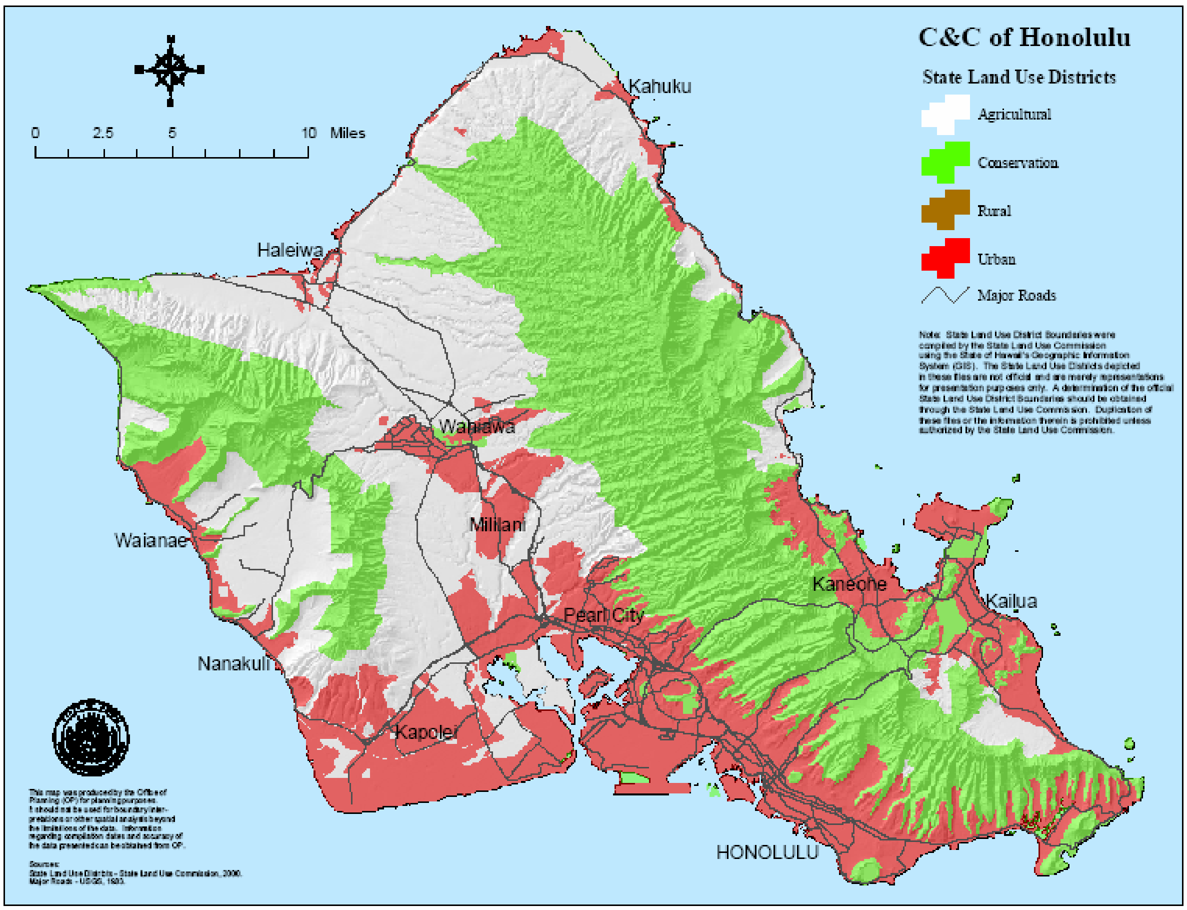


Figure 2.1 *Island of Oahu with State Land Use Districts shown: Agricultural-white, Conservation-green, Rural-dark red, Urban-bright red. Image used with permission from State Land Use Commission, using State of Hawaii's Geographic Information System (GIS).*

As stated above, the Island of Oahu has the greatest consumption of diesel fuel. Producing enough biodiesel to meet the demands of electricity generation, industry, transportation, and agriculture will require substantial parcels of land, capital investment, and willing, risk-taking farmers. With consumption of over 180 million gallons (693 million liters) of diesel in 2004, the amount of biodiesel necessary to formulate mixes of B2, B5, and B20 would be greater than 3.6 million gallons (13.6 million liters), 9 million gallons (34.1 million liters), and 36 million gallons (136.3 million liters), respectively. The necessity to start with small scale production combined with the high rates of consumption suggests that Oahu would best be able to transition to biodiesel through a slow process, beginning with mixing petroleum diesel with biodiesel to a B2 mix, followed by a B5 mix. Considering current technology and existing land constraints, getting Oahu's diesel consumption to the B20 mix will be challenging.

Oahu has approximately 128,800 acres (52,150 hectares) of land classified as Agricultural, under the guidelines of the State Land Use Commission (DBEDT, 2005). In 2002, Honolulu County had over 70,000 acres (28,350 hectares) of farmland, with 29,100 acres (11,800 hectares) in cropland. Areas of Oahu classified as such are shown in Figure 2.1. To produce row crops such as soybeans, prime farmland is needed and much of that farmland is in the production of truck crops, pineapple and seed corn. The pineapple industry still occupies over 20,000 acres (8,100 hectares) of land, with about half of that being harvested annually (DBEDT, 2005). With Del Monte Fresh Produce's decision to halt pineapple production in Hawaii, which includes Kunia (just west of Mililani-Town) in 2008, over 5,000 acres (2,050 hectares) of land under lease but also for sale by Campbell Estates could be utilized for a biofuel crop.

These pineapple lands and the former sugarcane lands on North Shore (Waialua southward to Wahiawa) from Oahu Sugar Company are the only lands on Oahu that have ideal growing conditions and in-place infrastructure for producing row crops. Row crops such as soybeans will require relatively flat lands on highly-productive soils that are either supplied by plentiful rainfall or have access to irrigation ditches. Other forms of oil crops could be grown on more marginal lands that are currently producing small vegetables, fruits, melons, or livestock. Other lands designated as Agricultural on Oahu are too arid, wet, steep, or have some other limiting factor or combination of limiting factors dictating their non-use for row crops. A discussion of the soils found in the central part of Oahu (the Leilehua Plateau) and the North Shore areas follows.

Five agronomically significant soil types, or series, are found in this region of Oahu. These five are Kolekole silty clay loam, Kunia silty clay, Lahaina Silty clay, Molokai Silty clay loam, and Wahiawa silty clay. Within these five series, the phases (classification based on limiting properties of each) that would be most suitable would be the 'A' and 'B' phases, with slopes ranging from 0-8%. Some lands are also in the 'C' phase with slopes up to 15%, but they are not considered to be 'prime farmland'. Total acreage of these five soil series on Oahu is approximately 35,600 acres (14,420 hectares), making up over 27% of Oahu's agricultural land use district (Foote et al. 1972). These soils are highly productive, especially under irrigation, and receive from 20-25" of rainfall per year in the Molokai soils to 40-60" of rainfall per year in the Wahiawa soils. The Land Capability Classes for these soils (a rating system used by USDA-NRCS to determine potential productivity) are Class I and IIe (the '*e*' letter denotes that any qualities limiting production would be due to erosion) for irrigated lands on all soil phases. For non-irrigated sites, the classes range from Class IIe or IIc to Class IVc (the '*c*' denotes limitations due to climatic conditions, in this case, low annual rainfall).

Table 1. Land Capability Classes

Class*	Restrictions/Limitations**
I	No significant limitations restrict use.
II	Moderate limitations that may require conservation techniques be in place; slopes 0-8%, somewhat poorly drained, seasonal flooding, poor textural conditions, inadequate rainfall, shallowness.
III	Severe limitations that may reduce choice of plants and may require special conservation practices; potential for severe erosion, slopes up to 15%, excessive water, poorly drained, excessive stoniness, low water-holding capacity, limited rainfall, moderately low fertility.
IV	Very severe limitations affecting crop choice and requiring very careful management; slopes up to 25%, excessive drainage, potential for seasonal flooding, excessive stoniness, very droughty, low fertility.
V	Not likely to erode, but significant problems with fertility, stoniness, texture, tilth, wetness, droughtiness, or some other condition restricting crops. Can be used for woodland, wildlife, pasture or range.
VI	Generally unsuited for cultivation of row crops. Used for pasture, range, woodland and wildlife habitat; severe erosion potential, slopes up to 40%, extreme rockiness, limited rainfall.
VII	Unsuited for cultivation of row crops. Used for pasture, range, woodlands, or wildlife-may require conservation measures to remain sustainable; highly erosive, slopes up to 100%, excessive drainage, extremely low water-holding capacity, rock contents nearing 100%, crater areas with poor drainage.
VIII	Unusable for any commercial plant production. Used for wildlife, recreation, and esthetic beauty; prone to constant or unpredictable flooding, exposed stones cover greater than 80% of surface, marshes, steep mountainous slopes up to 100%, some coastal beaches.

*Soil classes are subdivided using letters: e (erosive), s (stoniness, shallowness, or sandiness), w (wetness) or c (climatic limitations). "I" has no subclasses, and "V" does not have subclass "e".
**Specific limitations are detailed by subclass denotation (see above *). Any of the listed limitations are only examples. Specific limitations for any soil series should be referenced in the USDA-NRCS Soils Database online at www.soils.usda.gov/ or in a local Soil Survey. Guidelines detailed are for Hawaii soils.

One growth factor to consider at this point is the need for irrigation to produce crops. Because of Hawaii's sub-tropical to tropical climate, it is possible to cultivate a wide variety of crops. In order for bioenergy crops to be a reliable and profitable endeavor, the development of arid condition-tolerant crops should be investigated. The lessened dependence on irrigated crops would lower costs of production and maintenance necessary to operate a large-scale plantation of biofuel crops. There is irrigation infrastructure already in place at some of these locations, so irrigation would be an option if absolutely necessary. Water availability must be taken into consideration before any long-term decisions are finalized. Oahu is a location where oil crop production could be studied, using research facilities run by the University of Hawaii-Mānoa (Poamoho Experiment Station) and Hawaii Agriculture Research Center (Kunia Experiment Station). These facilities would be capable of working with row crops, tree crops, irrigated crops, and un-irrigated crops. Neighbor islands also have suitable sites for research, and the use of sites across the State will assist in isolating specific crops that may be utilized at various locations.

Some of the areas with these highly productive soils are currently used by pineapple growers Del Monte and Dole for pineapple production, but, as stated above, Del Monte will be closing production in 2008, freeing up about 5,000 acres (2,050 hectares). Livestock producers and small-scale growers of crops such as avocados, papaya, corn, citrus fruits, taro, tomatoes, melons, and other vegetable crops dot this region of Oahu because of the land suitability for efficient production. The primary landowners for these areas are large private landowners with more than 5,000 acres; e.g., Dole Food Company, Inc. (Castle & Cooke), and Campbell Estate, with whom Del Monte's lease will be expiring (Juvik and Juvik, 1998). Altogether, there may be up to 8,000 to 10,000 acres (3,200 to 4,100 hectares) available (after Del Monte ceases operation) for development of biodiesel row crops in Central and North Shore Oahu. It is likely that there will be serious competition for the production on these lands, especially as the State continues to try to meet demand for food and energy self-sufficiency.

One region of Oahu that could be utilized for oil crops that would require very little moisture would be the area just east of Waianae and Nanakuli on the Leeward Coast. With very low annual rainfall, these areas may well serve as lands for developing crops that are less water-intensive in their production, as compared to traditional row crops. As mapped by Foote et al. 1972, the dominant soil types in this area include Lualualei clay and Lualualei stony clay with 0-8% slopes heading up into the Waianae Range. These Lualualei soils have Land Capability Classes of IIIe and IIIs (the '*s*' denotes very stony soils) under irrigation and IIIs and VIs for un-irrigated soils. The VIs would normally prohibit any crop production, but if crops adapted to arid environments were installed, survival and productivity could still be realized with proper management on what are otherwise considered marginal to unusable agricultural soils. Other soils in this region of Oahu include small areas of Mamala stony clay loam (IIIs and VIs, with and without irrigation, respectively) and Pulehu clay loam (Class I or IVc with or without irrigation, respectively). Dry areas will require some irrigation to remain productive year-round, and any conversion facility built would need to have a sustainable, reliable feedstock, readily available water, and access to operational and distribution infrastructure. The use of arid and semi-arid lands for biodiesel manufacturing must consider availability of these resources.

Kamehameha Schools' land on the North Shore of Oahu, from Haleiwa northward to Waimea and inland to the Koolau Range, would provide an excellent location for potential oil crop production. With annual average rainfall ranging from 35" to 60", a large number of crops could be productive on these lands. An area of approximately 6,500 acres (over 2,600 hectares) of this land has productive soils and the topography necessary for large-scale crop production. Soils in this region are mainly Wahiawa silty clays, and small areas of Manana silty clays, Leilehua silty clays, and Paaloa silty clay are interspersed throughout the area. These soils are classified as Class I, IIe, IIc, and IIIe with and without irrigation. Access to irrigation water on Kamehameha Schools' land would come from old irrigation ditches used by sugar plantations in the past. These irrigation ditches may need some repair before implementing plantings of oil crops. Even without irrigation it is believed that these lands would provide a suitable environment for a variety of potential oil crops. Access to Kamehameha Schools' lands along the North Shore is by Kamehameha Highway, connecting the lands to all population centers on the island. The areas that would be utilized for crop production have been used for sugarcane and pineapple in the past, and old field roads would be in place to access and travel across the lands. The relative location of Kamehameha Schools land to the few small livestock operations on Oahu also provide any production scheme easier access to markets for co-products.

2.2 Island of Maui

Maui consumed a total of over 22.2 million gallons (84 million liters) of diesel fuel for highway and non-highway use in 2004, with the majority for non-highway use (DBEDT, 2005). To supply this amount of diesel with a 2% mix (B2), approximately 444,000 gallons (1.7 million liters) of biodiesel would be necessary. Maui currently has production of biodiesel totaling nearly one million gallons per year, using waste vegetable oil (WVO) by Pacific Biodiesel (King, 2006). This WVO is converted into straight biodiesel, or B100. This B100 is blended into mixes used in vehicles, and it is sold as straight B100 for converted diesel vehicles. To create biodiesel mixes such as B5 or B20, Maui would need to produce 1.11 million gallons (4.2 million liters) or 4.44 million gallons (16.8 million liters), respectively, from oil crops. A mandatory B20 blend replacing all diesel fuel consumed on Maui would replace the equivalent of over 493,000 barrels of petroleum, and B5 would replace over 123,000 barrels.

Maui offers more potential land available for oil crop production than does the Island of Oahu. With a smaller population, and less urban areas, agricultural lands are widespread across Maui. The potentially available land covers large contiguous areas with a variety of growing conditions. Land classified as 'Agricultural' on Maui totals almost 245,000 acres (99,200 hectares), as of December 31, 2004 (DBEDT, 2005). Land in farms totaled over 256,000 acres (104,000 hectares), as some farms, especially ranches, own lands that cross into 'Conservation' Land Use Districts. This overlap means that land on Maui for production of any new crops may result in some existing farming operations switching crops. Over 42,000 acres (17,000 hectares) is occupied by sugarcane, Hawaiani Commercial and Sugar Co., and pineapple, Maui Land and Pineapple, Inc. Much of their production is on highly productive lands. Other large agricultural operations are ranching and include Haleakalā Ranch Company (almost 32,000 acres), Ulupalakua Ranch Company (over 16,000 acres), Kaonoulu Ranch Co. Ltd. (7,700 acres), and Kaupō Ranch (5,700 acres). Most small farms on Maui produce vegetables, melons, fruits, and nursery and flower products. Other landowners with significant real estate on Maui zoned as Agricultural Lands include subsidiaries of Alexander and Baldwin, Inc., Campbell Estate, AMFAC JMB, HI, Inc., landowners with a few 1,000s of acres, and Hawaiian Home Lands.

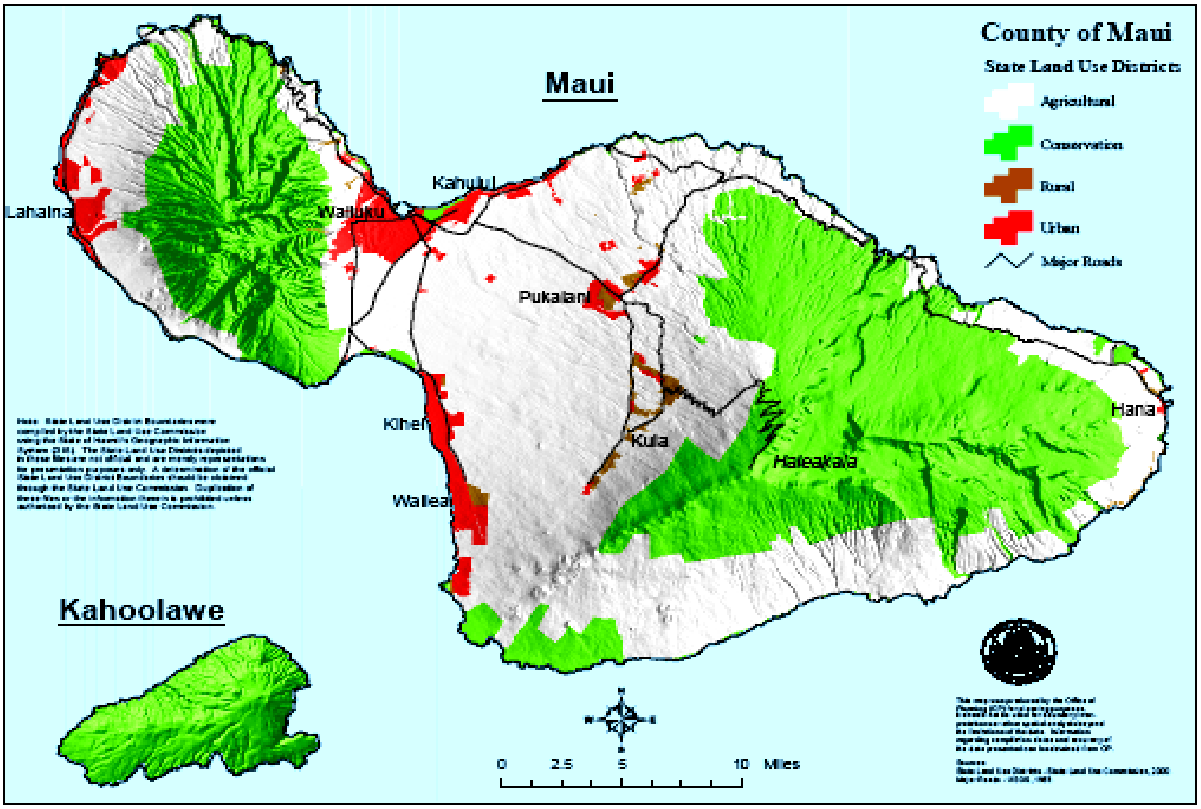


Figure 2.2 *Island of Maui with State Land Use Districts shown: Agricultural-white, Conservation-green, Rural-dark red, Urban-bright red. Image used with permission from State Land Use Commission, using State of Hawaii's Geographic Information System (GIS).*

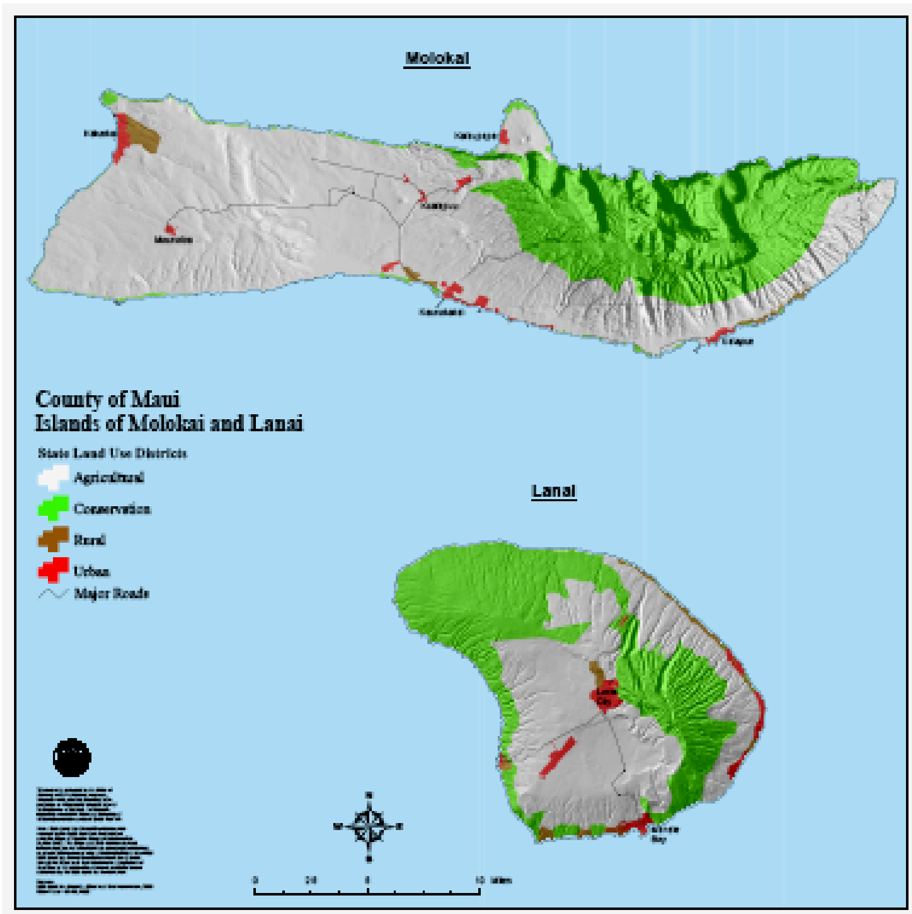
Establishing an efficient production scheme among many diverse landowners will require cooperation from both large and small landowners. Utilization of surface water for irrigation has been a growing concern on Maui for several years, so crops with low irrigation requirements in terms of irrigation should be the primary source of biodiesel from oil crops on Maui. Lands to be focused on for this report will focus attention toward areas not currently in production, as it is more likely that those areas will be accessible for oil crop production. Areas for consideration are: 1) West Maui, along the coastal areas just east and north of Lahaina towards Kahana and southward to Olowalu, and 2) Central Maui, on the upper western slopes of Mt. Haleakala in the Kula region.

The West Maui area considered is former sugarcane land of AMFAC, land of Maui Land and Pineapple, Inc. and smaller parcels owned by Kamehameha Schools, small landowners, and the State of Hawaii (Juvik & Juvik, 1998). The soils of this area are variable but have high productivity. Kahana and Lahaina silty clay soils dominate the northern part of this area from Kahana southward to Kaanapali. Along the coast of this portion of Maui are Jaucas sandy and Ewa silty clay soils and the upland areas to the east of Kahana have Alaeloa silty clay soils. All of these soil types have been used for production of row crops in the past, mainly sugarcane and pineapple. Much of this land is currently being leased by the seed corn industry, and coffee occupies approximately 200 acres (80 hectares). Slopes in these areas range from less than 3% in some coastal areas up to 25% in the uplands. Land capability classes for these soils are from IIe under irrigated conditions to IVe for un-irrigated soils in the higher elevations. Precipitation along this portion of Maui's west coast ranges from 20" to 60" annually, depending on relative location within the landscape.

Continuing along the west coast of Maui, from the area near Kaanapali, the Kahana soils disappear, giving way to Wahikuli silty clay and stony silty clays. Small areas of Molokai silty clay loam can be found just east of Kaanapali, and Lahaina and Alaeloa soils continue to be found in the upland areas heading southward to Lahaina. The Ewa soils dominate the coastline where beaches are not present. Just south of Kahoma Stream, the Wahikuli, Lahaina, and Aleloa soils change to Wainee very stony silty clays. These Wainee soils continue down the coastal and upland areas to Launiupoko Point, and Pulehu clay loams develop towards Olowalu and beyond. The Wahikuli soils and Wainee soils range in land capability classes from IIe to VIs, but they have been used extensively for irrigated sugarcane in the past. The rainfall for these areas is 10" to 20" annually. This limiting factor would greatly influence any crop chosen for production on West Maui. The Pulehu soil is very productive when irrigated, classified as I, IIe, or IIs, and has been used for sugarcane previously. These areas of West Maui could be used for row crops or tree crops, depending on available water and access to lands that may already be producing other commodities. The only major transportation route connecting the west coast of Maui to the rest of the island is Honoapiilani Highway. This highway is capable of handling heavy truck traffic that would be associated with the transport of harvested seed for processing or finished products of biodiesel. This one road is susceptible to heavy traffic and backups, so this route would need expansion or tight controls put in place on allowable transport times and equipment.

The second area for consideration is currently in ranchland, with a few small operations growing nursery crops and fruits and vegetables. Primary landowners in this region of Maui are Campbell Estate, Koanoulu Ranch Co. Ltd., Haleakala Ranch Co., small private landowners, the State of Hawaii, and Hawaiian Home Lands (Juvik & Juvik, 1998). It is situated along the low, western slopes of Mt. Haleakala, where rainfall is light and elevations range from 1,000 to 6,000 feet above sea level. The land here is primarily suited for pasture, but tree crops could be grown in these areas where intense field preparation and row-cropping are impossible. An integrated agro-forestry approach could fit this region, allowing ranchers to continue to graze livestock under and between the canopies of tree crops. The area being considered is a very large parcel of land (over 20,000 acres) that could be utilized in some fashion for biodiesel production. The predominant soils in this area have not been mapped extensively, but some general characteristics have been documented (Foote et al., 1972). Soils include Kamaole very and extremely stony silt loams, Keawakapu extremely stony silty clay loam, Kula loam and very rocky loam, Kaipoioi very rocky loam, Waiakoa very stony silty clay loam, and Waiakoa eroded stony silty clay loam. These soils have land capability classes of IVe, VIs, and VIIs, making them very marginal in terms of row crops that require irrigation and mechanical harvest, but potentially suitable for arid-land crops that produce high oil-content seeds. The eroded and rocky land could benefit from being converted into tree crops, as they have been shown to improve degraded lands by stabilizing slopes (Dudley, 2006). Rainfall on this face of Mt. Haleakala is limited, with only 10" to 40" falling annually, with most areas receiving between 15" and 25". Slopes in this area are relatively gentle for a mountain-side, generally ranging from 3% to 25%, with some areas up to 40%. Access to this area is provided by Kula Highway, which runs to the North Shore and back into Kahului. Department of Hawaiian Home Lands occupies very marginal lands in this area, and their inclusion in supplying land for oil crops could benefit multiple sectors of society and the economy.

2.3 Islands of Molokai and Lanai



shown: Agricultural- used with permission from State Land Use Commission, using State of Hawaii's Geographic Information System (GIS).

Molokai and Lanai are two islands that make up part of Maui County. Molokai has a total land area of about 260 square miles, or 165,800 acres (67,100 hectares), over 110,000 acres of which are classified as Agricultural by the State Land Use Commission (DBEDT, 2005). Lanai is the sixth-largest island in the State, with a total land area of 90,500 acres (36,600 hectares), or over 140 square miles. Of these 90,500 acres, over half is classified as Agricultural by the State. Molokai and Lanai have small populations, with approximately 7,500 and 3,100 residents, respectively. Minor areas of urbanization are located on each island, and the consumption of petroleum products is very low compared to other islands in Hawaii. Exact figures for petroleum usage on Molokai and Lanai are unavailable through DBEDT resources or from Maui's Economic Development sources, but in 2004 over 22 million gallons (over 83 million liters) of diesel fuel were burned for non-highway and highway use combined for all of Maui County. It can be assumed that less than one-fourth of this total was consumed on Molokai and Lanai combined. Molokai and Lanai are mostly rural areas with little urban development.

Molokai and Lanai each have distinctive landscapes that separate them into various land use areas. Molokai's eastern end is rugged and mountainous with the northern edge being mostly inaccessible. Central Molokai makes up about 20% of the land area, with 15,000 acres (over 6,050 hectares) that were once used for pineapple. The remainder of Central Molokai is used for pasture by large ranching operations. West Molokai has been used for pineapple cultivation, and the majority is used for pasture (Foote et al., 1972). Molokai receives an average of 30 inches of rainfall on average each year. This total varies across the island, with greater amounts of rain falling on the mountainous eastern side where Kamakou rises to nearly 5,000 feet above sea level. Thus, Central and West Molokai would provide the best lands for large-scale production of oil crops.

Lanai was formed by a shield volcano, and it has elevations over 3,400 feet above sea level on the eastern side of the island. To the southwest and west of this peak, the Central Plateau of Lanai was once the location of the world's largest pineapple plantation. The north side of Lanai has severely windblown soils, and the western and southern edges of the plateau below 1,200 feet of elevation have severely eroded and rocky soils. The Central Plateau is the only suitable area on Lanai for significant agricultural production. Lanai receives very little precipitation, as its windward side is shielded from prevailing tradewinds and moisture by the leeward coast of Maui. No perennial streams exist on Lanai, and irrigation and domestic water must be taken from lava dikes found at high elevations (Foote et al., 1972).

Land ownership on Molokai's areas suitable for oil crop production is variable. The majority of lands in Central and West Molokai are Hawaiian Home Lands, owned by Molokai Ranch, and small tracts owned by other private landowners. As of 1996, Molokai Ranch held over 52,000 acres (over 21,000 hectares), all of which were located in Central and West Molokai (Juvik & Juvik, 1998). Much of the land classified as Hawaiian Home Lands has been propositioned to be used for sorghum cultivation. This sorghum would be used to supply a major ethanol production facility. If Molokai lands are converted into ethanol-producing crops, the potential for biodiesel crop production is limited by land and water resources available. Lanai is primarily owned by Castle & Cooke, with only very small areas of land being held by small landowners.

Molokai has approximately 23,000 acres (9,300 hectares) of suitable land for pasture and cropland. The great majority of this land is comprised of Lahaina silty clay, Hoolehua silty clay, Molkai silty clay, and Holomua silt loam soils. Each of these soil types are classified as IIe and IIIe with irrigation and IIIc and IVc without irrigation. Molokai has the Molokai Irrigation Ditch system (MIDS) that has been renovated and repaired over the previous decade. It has an annual flow of 1.2 billion gallons (4.5 billion liters) of water, serving over 3,000 acres (1,200 hectares). The MIDS could be utilized for production of biodiesel crops. However, since existing crop production already competes for water, utilization of drought-tolerant crops is recommended on Molokai.

Lanai has very little irrigation water available for extensive crop production, even though it was once home to the world's largest pineapple plantation. Soils that would be cultivated on Lanai are Lahaina silty clay, Molokai silty clay loam, Waihuna clay, and Uwala silty clay loam. These soils are classified as IIe soils under irrigation and IIIc and IVc without irrigation. Total land area of these soils on Lanai is approximately 12,000 acres, or 4,800 hectares (Foote et al., 1972). Production of biodiesel crops on Lanai would supply the small number of residents with sufficient fuel for electricity generation. The ability to generate enough productivity with limited water for cropping is the primary roadblock on Lanai. As with Molokai, isolation of the most drought-tolerant crops requiring minimal inputs would be ideal for biodiesel production on Lanai.

Molokai and Lanai have relatively undeveloped road systems. Of the six developed islands of Hawaii, these two islands have the least advanced infrastructure. Roads remain unpaved in many areas of each island, and transport of harvested crops and processed fuels may prove somewhat more difficult than on other islands. Molokai's primary roads are State Highway 46 from Kaunakakai to Mauna Loa, which runs through a vast agricultural area, and Farrington Avenue, a road traveling from Kualapuu through Hoolehua and into open lands in the northern areas of Central and West Molokai. Aside from these two primary arteries, many small paved and unpaved roads traverse the rural and agricultural parts of Molokai. Lanai also has two primary avenues for transport across agricultural lands. State Highway 44 (Kaumalapau Highway) runs from Lanai City westward to Kaumalapau Harbor. State Highway 441 (Manele Road) and Miki Road intersect the agricultural lands south of Lanai City. As with Molokai, Lanai has many small paved and unpaved roads that travel deeper into the open lands. Transport of equipment, harvested crops, and processed fuels will be more expensive on both Molokai and Lanai.

2.4 Islands of Kauai and Ni'ihau

The Island of Kauai is the northernmost island with significant population and consumption of diesel fuel. Kauai is a predominantly rural island with a long history of agricultural endeavors. Kauai's total usage of diesel fuel in 2004 was approximately 19 million gallons, or almost 72 million liters (DBEDT, 2005), with nearly 85% of that for non-highway purposes. Kauai has the lowest consumption levels of all counties in Hawaii. Meeting the need for biodiesel on Kauai may be more feasible than any of the other Islands, with the exception of any work that were to be done for self-sufficiency on Molokai, Lanai, or Ni'ihau. To produce B5 or B20, Kauai would need to produce 950,000 or 3.8 million gallons (3.6 million or 14.4 million liters) of biodiesel, respectively. Total land designated for Agricultural purposes on the Island of Kauai was 139,000 acres (over 56,000 hectares) as of December 31, 2004 (DBEDT, 2005). Similar to Maui, Kauai has more land in farms than land actually designated as 'Agricultural', with over 150,000 acres (60,000 hectares) in farmland in 2002 (DBEDT, 2005). Approximately 30,500 acres (12,300 hectares) of farmland were in cropland in 2002, leaving most other agricultural lands in ranches and greenhouse and nursery operations. Primary landowners on Kauai are the State of Hawaii, Robinson Family Partners, Grove Farm Company, Alexander & Baldwin, AMFAC JM, HI, Inc., and small, private landowners.

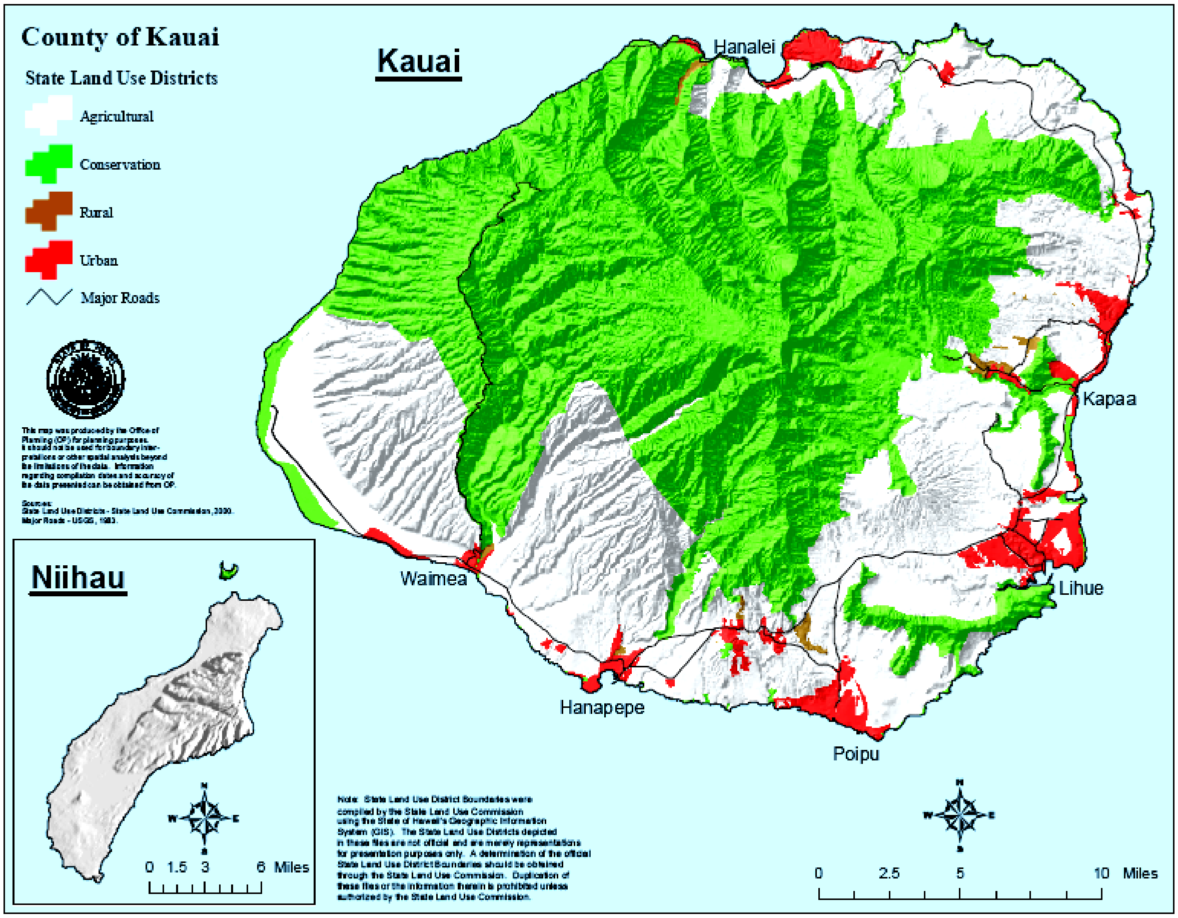


Figure 2.4 *Island of Kauai with State Land Use Districts shown: Agricultural-white, Conservation-green, Rural-dark red, Urban-bright red. Image used with permission from State Land Use Commission, using State of Hawaii's Geographic Information System (GIS).*

As shown in Figure 2.4 above, 'Agricultural' lands almost encircle the central highlands of Kauai, taking up most of the coastal lands from the Mana region on west Kauai southward to Hanapepe, around to Lihue, and along the eastern coast and the North Shore to Hanalei. Kauai has many areas of highly productive land, much of which has been used for sugarcane in the past. Kauai has had some of the highest sugarcane yields ever recorded, with fields producing over 20 TSA (tons sugar per acre). Major agricultural production on Kauai is of sugarcane along the southern coast, ranchlands around much of the eastern side, and taro and other vegetable and fruit crops on the North Shore. Areas that could potentially serve as biodiesel crop cultivation zones are the Mana Plain, the region south of Kōloa, near the Waita Reservoir, and parts of the Lihue Basin.

The area around the Mana Plain makes up from 5,000 to 6,000 acres (2,000 to 2,500 hectares) of land, in what was once irrigated sugarcane land. A variety of agricultural endeavors currently take place in this region of Kauai. The area stretches from north of Mana at the convergence of the mountainous slopes and the sandy beaches that continue around the isolated northwest coast of the island to just north of Kekaha on the southwest coast. It is directly adjacent to the Bonham Landing Field and other military installations that hug the West Coast of Kauai. Primary land ownership in the Mana region is by the State of Hawaii. Associated soils in this area are Jaucas loamy fine sand, Kaloko, Lualualei, and Nohili clays, Kekaha clays and silty clays, and old Fill Land. These soils have widely variant qualities, but all were once used for irrigated sugarcane. Their capability classes range from Class I to IIIw to IVs under irrigated conditions to Vw and VIs for un-irrigated areas. Limiting factors in this area range from shallow water table, lack of rainfall, mild alkalinity, difficult workability, and poor drainage in some sites. Rainfall averages 18" to 30" on a yearly basis. The area is a coastal plain with relatively flat topography, with slopes no greater than 5-6%. The lack of rainfall could make this area ideal for dryland crops in an easily accessible locale. Access to the Mana Plain is via Kaumuali'i Highway, which runs from Mana around the southern coast all the way to Lihue. Much of these lands are currently in high value seed production, especially corn. Annual oil crops could possibly be utilized in rotation, but facilitating dual-use of these lands may prove difficult.

The second region for possible biodiesel crop development is just south and east of Kōloa. It stretches down to Poipu and Makahuena Point on the southern coast around to near Kamala Point. The area was once farmed by Grove Farm and McBryde Sugar Co. for sugarcane, and it encompasses approximately 1,400 acres (560 hectares). Land ownership is mainly by small, private landowners, and some land is still under the ownership of Grove Farm. The primary soils for agricultural production are Kalihi and Keana clays (classified as IIIw), Koloa stony silty clay (class IIe, IVe when un-irrigated), and Waikomo stony silty clay and very rocky silty clay (classes IVs and VIs, respectively), and old Fill Land where cane mill slurry, dredged solids, and other wastes were concentrated (Foote et al., 1972). Most of this land has been used for irrigated sugarcane and pasture land. The two clay soils are very deep, somewhat poorly drained, support very deep rooting, and are difficult to work. The stony and rocky soils are moderately deep (≤ 40") to shallow (< 20"), but they have plentiful available water holding capacity. Some rock outcropping is present in the Waikomo soils. Rainfall on this part of the island ranges from 40" to 75" per annum. In the areas without high rock content, field crops could be grown here with few irrigation requirements, or tree crops such as oil palm could be grown over large acreages. Access to the Kōloa agricultural lands is by State Road 52 to Koloa from Kaumuali'I Highway, and from Kōloa, Weliweli Road heads east and south through the farmlands and Poipu Road goes south to the town of Poipu. The area has quick access to Lihue, the main population and economic center of Kauai.

Another part of Kauai that could be utilized for biodiesel crop development is in the Lihue Basin, directly north of Lihue to the South Fork of the Wailua River and west of Kalepa ridge, north of Hanamaulu, and from the South Fork Wailua River to the North Fork Wailua River. This area has been used for sugarcane, pineapple, pasture, truck crops, and other miscellaneous fruits and vegetables. Lands here are primarily owned by small, private interests and AMFAC JMB, HI, Inc. The total land area for this potential site is between 1,600 to 2,000 acres (650 to 800 hectares). Predominant soil types in these small upland plots are Kapaa and Lihue silty clays, Lihue gravelly silty clay, and Puhi clay loam. Land capability classes are IIe or IIIs for all soils under irrigation or not (Foote et al., 1972). The soils are deep and acidic, they allow for deep rooting depths, and each can support a wide variety of crops. The average annual rainfall for this part of Kauai ranges from 60" up to 100" in the most extreme cases. These soils could support row crops that are tolerant of high rainfall or fast-growing crops that could have multiple harvests within one year, as enough moisture is available without irrigation to produce several crops yearly. Such crops would need to be grown in a rotation to avoid diseases, heavy bird predation, and depletion of nutrients in the soil. Tree crops that withstand high rainfall climates could thrive in this area, and those that require little in the way of chemical additions and pest control compared to row crops could be grown without affecting much of the natural scenic beauty of Kauai. This area is easily accessible using Maalo Rd. (State Highway 583) from Kuhio Highway out of Lihue. Close proximity to the island's main hub is also an advantage of this location.

Ni'ihau is the least populated of the seven main Hawaiian Islands. At approximately 70 square miles, it is also the smallest of the inhabited islands. Commonly referred to as the "Forbidden Isle," Ni'ihau is owned by the Robinson Family (of Gay & Robinson, Inc.), and access to the island is granted through them. A small population of approximately 200 people currently inhabits the island. All residents are of native Hawaiian heritage, and they live in relative isolation from the rest of the world. The entire island is zoned as Agricultural, and it was formerly occupied by Ni'ihau Ranch. The ranchlands were home to cattle and sheep, but the ranch shut down in 1999 from a lack of profitability. Small villages are located along coastal areas of the island.

Numbers on fuel consumption for Ni'ihau are not readily available. Small naval facilities are located on Ni'ihau, and the U.S. Navy takes responsibility for supplying fuel to the population. The local population utilizes diesel fuel for generators that supply electricity as needed and automobiles and other equipment as needed. No data is available for soils or land types on Ni'ihau. It is known that annual precipitation on Ni'ihau ranges from only about 8-20" annually, averaging about 12". Freshwater is collected through dikes that store rainwater from the wetter side of the island. It is believed much of the island is scrubland populated with small woody shrubs and trees. The island is mostly wind-blown, and its relative location to Kauai prevents it from receiving significant rainfall from windward showers.

Soils are believed to be shallow, rocky, relatively infertile, droughty, and have poor workability. No soil survey has been conducted on Ni'ihau, so before any crop production could commence, information would be needed from the Robinson family and tours of available land would need to be carried out. If initial work was begun on Ni'ihau, local residents would be instructed on operations needed to maintain the crops. Only a small amount of land would be needed to supply the local population and naval operations with the fuel necessary annually. Sufficient collected freshwater would be the primary concern for crop production. If crops could be isolated to utilize coastal areas with brackish waters and groundwater with high salinity, there would be potential to produce biodiesel on Ni'ihau.

2.5 Island of Hawaii

The Island of Hawaii (hereon referred to as Big Island to avoid confusion) is the largest island in the Hawaiian chain. Total diesel consumption in 2004 was almost 40 million gallons (over 150 million liters), ¾ of which was for non-highway use. To supply the needs of Big Island's diesel consumption in the form of a B5 or B20 blend, 2 million or 8 million gallons (7.6 million or 30.3 million liters), respectively, of biodiesel would need to be produced. Big Island occupies over half the State's total land area and over 60% of the lands classified as 'Agricultural' by the Land Use Commission (DBEDT, 2005). Over 1.2 million acres (485,000 hectares) of land are available for agricultural endeavors on Big Island. Because of such large areas of agricultural lands, it may be possible to produce enough biodiesel to completely replace petroleum diesel in the near-future. Big Island could possibly even be tapped for production of biodiesel for export to other islands, if deemed economically feasible to ship out liquid fuels across the inter-island channels. In 2002, there were over 3,000 farms on Big Island, totaling more than 820,000 acres (330,000 hectares), 90,000 acres of which were in cropland. Over 55,000 acres were harvested that year. Primary crops produced on Big Island are vegetables, herbs, melons, papaya, coffee, macadamia nuts, and flowers and nursery products. With the extensive land resources available on Big Island, finding land for production of oil crops, especially trees, should not be difficult. The selection of crops to be cultivated in those areas will be of primary importance.

Three areas on Hawaii Island have been selected for this assessment. The areas have unique climatic, soil, and topographic conditions. Because of the large ranching operations on the island, selection of regions for oil crops was limited to areas of relatively little ranching, old sugarcane lands, and marginal lands unused for crops previously. If the ranching industry is willing to sacrifice some of their pasture lands, it is expected that more flexibility would be allowed to the State for encouraging the production of biodiesel. A ranch sacrificing its lands for biodiesel production is unlikely without added incentives or without having an agroforestry scheme devised which provides for a dual use of the land. Utilization of old croplands and marginal land is likely to be the initial component of Big Island's conversion to biodiesel. Ranches would benefit from the by-product, feed, associated with biodiesel crops.

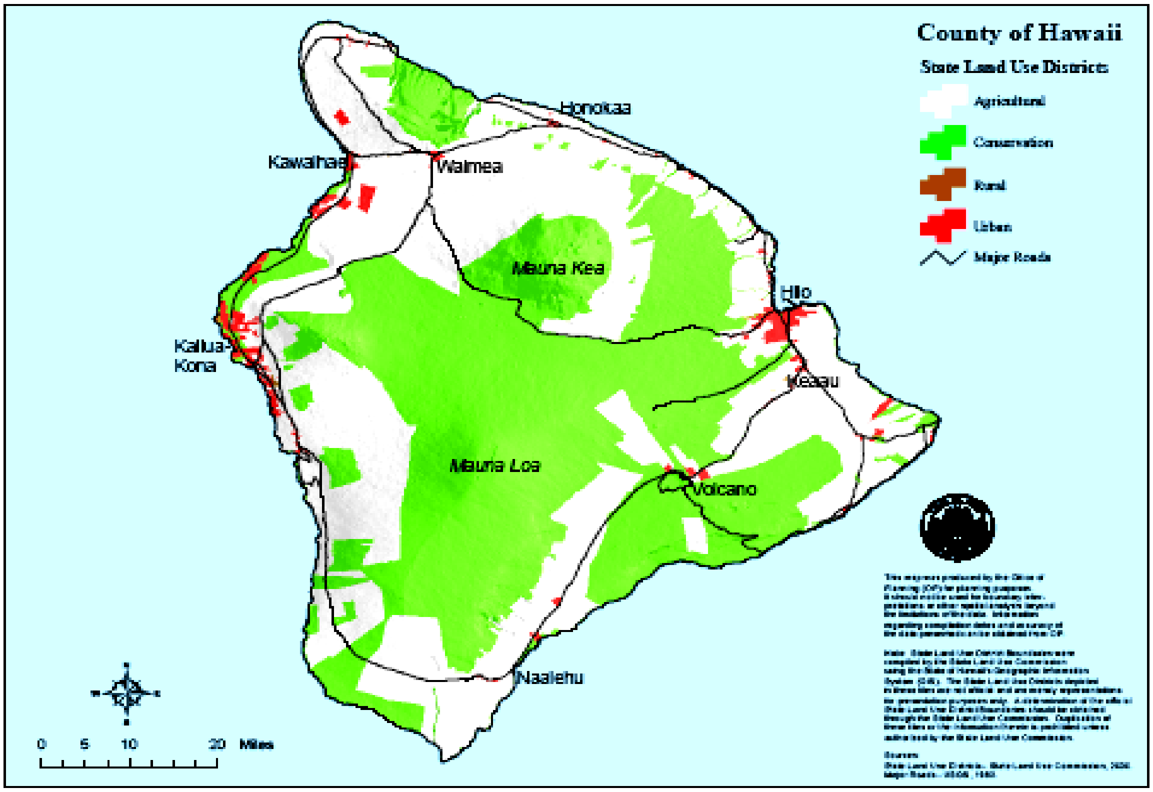


Figure 2.5 *Island of Hawaii with State Land Use Districts shown: Agricultural-white, Conservation-green, Rural-dark red, Urban-bright red. Image used with permission from State Land Use Commission, using State of Hawaii's Geographic Information System (GIS).*

The first region to be isolated was the area from Waimea northward to the coast, heading southeasterly down the coastline towards Hilo. This area was almost entirely dominated by sugarcane prior to the collapse of the sugar industry in the 1980's and 1990's. Some small areas of ranching and livestock production also persist in these locations, but the quality of the land is high for Big Island, with relatively well-developed soils and access to water, mainly via the Hamakua Ditch. Landowners in this region are the State of Hawaii, Kamehameha Schools, C. Brewer & Co., and other private landowners and small areas designated as Hawaiian Home Lands (Juvik & Juvik, 1998). It is estimated that this portion of the island covers a land area close to 60,000 acres (24,000 hectares). Accessibility to this part of the island is via State Highway 19 (Mamalahoa Highway), which runs through the entire area selected, connecting the county seat of Hilo to the rest of the island. The rainfall on this windward side of the island averages from 100" to over 200" in some places. With such high amounts of moisture, more flexibility exists to utilize crops that require significant amounts of moisture. Harvesting operations will also have to be adaptable to such moist conditions, remaining unaffected by extremely heavy and persistent rains. The soils found from the inland, upland areas near Waimea to the coast, and down to Hilo are Akaka, Honokaa, Hilo, Kaiwiki, Kukaiau, Ookala, and Paauhau silty clay loams (Sato et al., 1973). These soils are rated very similarly with regards to land capability classes, with all being graded as IIIe or IVe, depending on how much slope is present. These soils are deep, well-drained, acidic, and historically proven to be productive in row crops (sugarcane). The rainfall and acidity are the two primary limiting factors to be considered during selection of crops for production in this area. The lands most suited for agricultural production in the Hamakua region are now planted with Eucalyptus and are close to the first harvest for timber purposes. The Hilo district is planted with many fruit and nut crops presently.

The second location for consideration is in the Puna District on the southeastern tip of the island. From east of Volcano and its surrounding Conservation lands, traveling eastbound up Highway 11 towards Glenwood and Kurtistown, southward to Pahoa and on down to the southern coast of the island is land mostly earmarked as agricultural by the State Land Use Commission (DBEDT, 2005). The areas surrounding Glenwood to Kurtistown are old sugarcane lands, and small areas of ranching, papaya, nursery crops, vegetables, and other miscellaneous crops dot this area on down to the coastline. Landowners here are Campbell Estate, Kamehameha Schools, small private landowners, the State of Hawaii, and W.H. Shipman, Ltd. The area is approximately 100,000 acres (40,000 hectares) in size, with significant portions of that already in established cropping systems. This region of the island is accessed using State Highway 11 (Hawaii Belt Road) to the old sugarcane land and Highway 130 south to Pahoa, continuing down Highway 137 to the southern coastline. Rainfall in this area of the island ranges from 90" up to nearly 200" per year. This area is also windward, resting on the eastern slopes of Kilauea, and it has many different microclimates and soil types. Old sugarcane soils in this area are Akaka, Hilo, Hilea, Ohia, and Olaa silty clay loams, with land capability classes of IIIe and IVs, mostly. There are some areas in this region of exposed lava flows of both A'a and Pahoehoe lava, and these areas could likely not be used for any production. The lands in the rockier areas that have been used widely for woodland and pasture consist of Keei, Keaukala, Malama, Opihikao, and Papai stony muck soils. This area is generally referred to as the 'Puna Rocks'. The land is not classified as having high potential for productivity, but its location and growing conditions could be adapted to by various tree crops such as oil palm. These soils are acidic and shallow, with areas of extensive rockiness at the surface. The rocky surfaces may inhibit effective trafficking on these soils, but the land could serve as a very valuable region of production for biodiesel if such problems are addressed through engineering developments.

The final area on Big Island for biodiesel crop production is in the southern Ka'u District near the southern tip of the island. Just west of the Ka'u Forest Reserve is a relatively under-utilized parcel of land some 25,000 acres (10,000 hectares) in size that stretches to an area that lies south and east of Papa. The portion directly adjacent to the reserve has been used for ranching, but a much larger area is designated for agricultural land use by the Land Use Commission (DBEDT, 2005). The primary land-holding group in the region is Walter C. Witte, et al., the Samuel Damon Estate, and some small portion may fall under State ownership and some small private landowners. Kamehameha Schools and another large landowner have bought significant areas of the C. Brewer lands near this region. Some of these areas have been planted to forestry crops that are productive and well-suited to the landscape and climate.

Access to this portion of the island is along State Highway 11, as it splits the area down the middle, creating a north half and a south half. The geographic location has this area positioned on the southern slopes of Mauna Loa on lands ranging from near sea level up to 7,000 feet above sea level. Average rainfall can be anywhere from 30"on the leeward facing parts up to 80" on the more windward slopes. This disparity would encourage a variety of crops be used if production were to ensue at this location. Most of the soils in this area are recommended for use as pasture or woodland. The soils are very rocky, and would be practically impossible to work, so it would be necessary to focus on tree crops for this location. The soil types will only be mentioned by name, as there is so much variance on the mountain slope that it would make a detailed listing cumbersome. Soils range from productive loams (class IIIe) to extremely stony muck-soils (class VIIs). These soils include Hanipoe, Kamoa, Mawae, Kiloa, Kona, and Puna soils that are all very shallow and have differing amounts of rock fragments. Most of these soils are shallow layers of organic material overlying A'a lava. More detail can be found in the Soil Survey for the Island of Hawaii, State of Hawaii by Sato et al., 1973.

3. Potential Crops for Oil Production in Hawaii

3.1 Soybean – *Glycine max*

Soybean is an annual crop grown in temperate, subtropical and tropical climates around the world, although it is a subtropical plant by origin. Soybean is grown around the world, and its primary producers are the United States, Brazil, Argentina, China, and India. During the 2001-02 growing season, almost 195 million acres (79 million hectares) were harvested worldwide (Conner et al. 2004). Soybean oil is the major edible oil in the world. Uses for soybean include as an edible vegetable, as a source for cooking oil, as a crop for pasture, fodder, or silage, and as a source for oils used in the manufacture of paints, linoleum, oil cloth, printing inks, soap, insecticides, and disinfectants (Roecklein et al. 1982). Soybean oil is the primary source for biodiesel production in the US, and an estimated 75 million gallons (over 283 million liters) of biodiesel were to be produced in 2005 (NBB, 2005). This total was more than 100 million gallons less than the total consumption of diesel fuel on Oahu in the same year.

Soybean plant

Soybean seedpods and seeds

The average oil content for soybeans is 18-20%, with protein content of 40%. In favorable conditions, a high yield of soybeans around the world is approximately 1,700 kg ha^{-1}, or 60 bu ac^{-1}. Many cultivars (cultivated varieties of plants) grown in mid-latitudes have performed poorly in tropical climates, with yields 30-60% lower in attempts to establish soybean in the lower latitudes. It is most often grown in climatic regions that also produce corn (*Zea mays*). It does not tolerate excessive heat or cold, and grows best on fertile, well-drained soils with pH ranges of 6.0-6.5. Soybean is a leguminous crop that, when grown on the same fields in rotation with other crops, will have increased yields because its symbiotic relationship with nitrogen-fixing bacteria supplies the soybeans and other subsequent crops with a natural source of nitrogen. Due to this self-sufficiency in N-production, the inputs required to grow soybean crops are potentially lower than many other oil crops which must be planted each season after harvest. The beans are produced in seed-pods, which are harvested by combine method. In past attempts at producing soybean in Hawaii, bird predation on seed-pods was a severe limitation on production capacity. Even though less N-fertilization is required because of the relationship with *Rhizobium sp.*, soybeans require a great deal of intensive management, ranging from weed control to specialized harvesting equipment not typically used in Hawaiian agriculture.

To produce soybeans on a large scale in Hawaii would require significant initial investments, including bringing in experienced growers, harvesting equipment, processing equipment (which will be a necessity for any production of biodiesel), and the development of best management practices (BMP's) to ensure stable production on a year-round basis. Mainland production of soybean biodiesel relies on high levels of crop productivity, because soybeans have a relatively low oil content of 20%. The decades of experience with soybean production, as well as development of new cultivars, especially 'Roundup-Ready' soybeans, allows for more efficient means of biodiesel production with a somewhat unproductive crop. In Hawaii, heavy use of herbicides to control competing weeds would be a continual problem. Repeated cultivation of soybeans on the same parcel of land can also promote diseases and insects, thereby reducing yields over time.

Cycling soybean in crop rotations has also led to higher yields in mainland agricultural systems. Large-scale operators in business growing soybeans for many years have invested significant funds into the harvesting equipment. Soybeans are harvested using standard combines such as those for harvesting wheat, oats, or corn. It is not uncommon to pay over $75,000 for a quality used combine; new combines can cost up to $250,000. Land preparation, planting, fertilizer, irrigation, and management equipment are already available on the islands, but expanded operations would require significant investment in new or used machinery and supplies. These investments would depend upon the size of each operation initiated. Very high volume operations can usually justify such expenditures.

Rough estimates of mainland soybean production range between 30-50 bushels per acre per year (Foreman and Livezey, 2002). The U.S. average for biodiesel yield for one acre is 40-50 gallons per acre (150-190 liters per acre) (NBB, 2005). Hawaii can grow any crop year-round, including soybeans. Hawaii would be able to produce almost three crops of soybean per year (12-14 months for three crops), but yields would be widely variable based on time of planting and location. Under BMP's, with bird predation not factored in, Ogoshi, et al. (1998) showed *simulated* soybean production on Oahu's North Shore ranging from 250 - 4,100 kg ha^{-1}, depending on cultivar, planting density, the time of year the crop would be planted, its supply of water, and its location. This level of variability in crop yields throughout a year should be of considerable concern to those who wish to implement continuous, year-round soybean production in Hawaii.

In the past, birds have destroyed entire test plots of soybean plantings on various islands, from Maui, to Oahu, to Kauai (Osgood, 2006). Recent trials on Maui conducted in private by Maui Land and Pineapple Co. showed bird predation to be the major limiting factor. The small plots installed were completely wiped out by birds soon after seedpods had formed (King, 2006). Bird predation can also be a major problem immediately after planting and germination of cotyledon leaves has taken place. The young growth is palatable to birds, and destruction of the plant at this stage causes a total loss for the individual plant. It is believed by some that large plots could produce plenty of soybeans for biodiesel, as the birds would only feed on outer edges of fields. Those in the research community feel that large fields of such crops will only encourage more birds to migrate to such areas and increase their populations (Santo, 2006; Uehara, 2006).

Excellent yields for an acre of soybeans in Hawaii would be about 35 bushels per acre, and even that may be high depending on the amount of bird predation that takes place. With three crops potentially producible in one year in Hawaii's climate, the best-case scenario for production would be 140 gallons of biodiesel per acre (215 liters per hectare). It is more likely that yearly totals for three crops in Hawaii would be closer to 100 gallons per acre (153 liters per hectare), based on one bushel of soybeans yielding 1.4 gallons of biodiesel (USDA-FSA, 2003). This total is relatively low compared to other potential crops that will not be as input-intensive from the production standpoint. Soybeans must be planted and harvested each season they are to be grown, increasing fuel consumption, and labor, equipment, and depreciation costs. Land costs would be established by landowners on a per acre basis, which would likely depend on quality of farmland and accessibility to irrigation ditches and reservoirs.

In an analysis on soybean economics in mainland agricultural systems, soybean farms with over 250 acres of production had production costs of approximately \$135 per acre, with revenues (after production costs) of \$147 per acre, \$168 per acre, and \$132 per acre for farms producing 250-500 acres, 500-750 acres, and >750 acres of soybeans, respectively (Foreman and Livezey, 2002). Foreman and Livezey broke down all soybean producers into three categories: low-cost, mid-cost, and high-cost. After careful evaluation of their methodology, it was determined that Hawaii producers would most likely fall into the 'high-cost' producing category. In the high-cost category, total cost of production was almost \$185 per acre for each crop. This estimate did not take land acquisition into account, as farms considered under this study were owned by the producers. Factor in land leasing or purchasing in Hawaii, and the production costs for soybeans will greatly increase. With revenues at only \$20.68 per acre, adding land costs would force the average 'high-cost' operation out of production in a matter of years. Even the 'low-cost' producers' revenues were only about \$221 per acre, which would likely pay for the necessary land, but it must be considered that these crops were grown for consumption, not energy purposes. The water costs alone would likely be greater per acre than the value of the crop, making the economics of soybean production in dry microclimates unfeasible.

3.2 Flax (linseed oil) – *Linum usitatissimum*

Flax has had a long tradition in mainland agriculture. Originally used for fiber (linen) and the oil produced by its seed (linseed oil), the demand for flax and linseed oil has decreased since the mid-20th century because of heavier reliance on petroleum products. Flax is a broadleaf plant that prefers cool growing seasons. Seeds are produced at stalk tips in small pods, containing on average 5 seeds per pod. Growth requirements are similar to those of oats and wheat. It is primarily grown in Russia, India, Argentina, Canada, and in the high plains regions of North Dakota and Minnesota in the U.S. Today, flax is most commonly used for its seed oil, which is fast drying and makes the oil suitable for paints and varnishes, but it has also shown various nutritional benefits. Flax also works well as an inter-crop to utilize fallow land (with rice, sugarcane, and peanut in India).

Straw from seed flax varieties has been used in the manufacture of upholstery cushioning, rugs, and paper (Duke 1983). Leftover seedcake remaining after oil extraction provides a high-value livestock feed, as well as dietary supplement for humans. Flax is a species with a low nitrogen requirement, and no specialized farm machinery is required to plant or harvest its seeds (the same equipment used in small grains can be used for such operations). Flax plants are tolerant to drought, grazing, herbicides, high pH, viruses and weeds. Competition with weeds in Hawaii's climate may be more difficult than in other more-temperate environments. Flax requires a cool temperate or subtropical climate with precipitation evenly spread throughout the growing season.

In 1961, a study conducted in Australia with sub-tropical varieties of flax from India tested time of planting on seed and oil yields. The tests utilized irrigation throughout the duration. It was concluded that yields significantly and progressively declined in plantings that were made closer to the onset of rising temperatures and increased day length (Beech and Morgan, 1963). The yields decreased due to reduced vegetative growth and a shortening of the flowering and seed maturation phases of the flax life-cycle. An Italian study tested planting densities to determine effects of densities, temperature, leaf area index, and rainfall on seed yield. During a hot, dry year, seed yields were less than 50% those of the previous year under more normal conditions (Casa et al. 1999). Casa et al. (1999) were able to get yields of up to 2 t ha^{-1} (194 bushels per acre) on a consistent basis under ideal growing conditions, regardless of planting density, and they suggest that yield reductions were most likely caused by high temperatures, which can cause yield losses through a hastened developmental rate and shortening of growth cycle with water shortage. Such data suggest that flax would work in Hawaii only under very intensively-managed conditions with careful attention to irrigation, temperatures, and planting dates. The Italian and Australian studies signal that flax might only be productive during cooler, wetter months in specific areas of the islands. Because flax could only be productive at certain times of year, it would need to be grown in rotation with another oilseed crop to maximize productivity of the land.

Flax plants in rows

Flax seeds or 'linseeds'

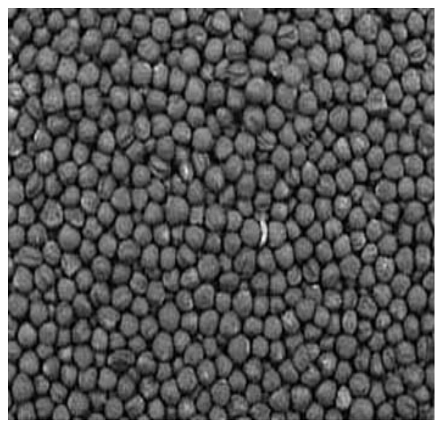
High-yielding flax varieties have shown the capacity to yield between 1,200-1,400 lbs ac^{-1} of seed. The flax seed is approximately 40% oil, and harvesting is done via combine. Flax can be grown for fiber, seed, or both. Varieties grown for seed tend to be shorter in stature than the fiber varieties (Thomas Jefferson Agricultural Institute, 2006). The growing season for flax is approximately 120 days. In the early 1900's the Hawaii Agricultural Experiment Station attempted trials in flax production for fiber, but yields of the seed proved to be more significant at 17 bu ac^{-1} (Crawford, 1937). That would equate to approximately 950 lbs ac^{-1}

(1 bushel = 56 lbs), and with improved methods of production that have been developed in the last 90 years, yields could be expected to be somewhat higher today. As seen in the study conducted by Casa et al. (1999), yields over ten times what were achieved in Hawaii in 1937 may be possible under ideal conditions. An attempt at developing a flax industry in 1851 in Hawaii was unsuccessful. Duke (1983) notes with caution that tests with linseed oil have shown much engine wear, causing several investigators to reject its use as a potential fuel oil.

3.3 Rapeseed – *Brassica napus* L.

Rape is a cruciferous crop that produces tuber-like rutabagas below ground and vegetation similar to kale above ground. The rapeseed is harvested for oil production, with an increasing demand for use as a biodiesel source worldwide. Estimated worldwide production of rapeseed for 2004/2005 growing seasons was 45.8 million metric tonnes (MT) (50.4 U.S. Standard tons) (FAO-UN, 2005). Rapeseed oil is also used in lubricants, illuminants, and soap manufacturing. It is primarily produced in Canada (known as canola oil) and Western Europe, but significant production also takes place in China. It is estimated that almost 45% of rapeseed production in the 2005/2006 growing season will be utilized as a source of biodiesel.

Rape plants in flower



Rape seeds

Rape plants need loose, fertile, well-drained soil, and fertilization elicits positive responses, as long as it is not placed in direct contact with the seed. The rape plant requires sunny days and cool nights for germination. It requires an approximately 90-day growing season, and it can be easily utilized as part of a double-cropping cycle, but it may not be productive if grown immediately following rape or mustard crops. It can be a slow-germinating crop, which will cause difficulty in out-competing weeds, thus reducing field productivity. The harvesting of rapeseed can be difficult, as moisture contents must be almost exactly 8%, where shattering may occur if the seed is too dry, and molding may occur if the seed is stored too moist.

Oil contents for rapeseed average between 37-50%, making it a high-yielding oil crop. Rape is not generally grown outside of temperate and sub-temperate climates, as there are many pathogenic organisms which can destroy a crop. Numerous fungi, virus-causing diseases, and insect pests can seriously reduce crop yields. This could be an important factor in the consideration for growing rape in Hawaii. In trials carried out in 1916-1917 by the Hawaii Agriculture Experiment Station, 'Dwarf Essex' rape showed good forage yields initially, but was eventually completely destroyed by cutworms (HAES, 1918). Although management conditions and pest control options are more readily available in modern agriculture, the potential for severe crop damage from tropical pests remains high. The development of varieties resistant to pest damage could alleviate some of these concerns.

Rapeseed yields can vary greatly from one region of the world to the next. Seed yields can vary from 900 to 3,000 kg ha^{-1}(800-2,600 lbs per acre), and yields of 1,500 kg ha^{-1} (1,330 lbs per acre) would yield approximately 500 kg (1,100 lbs) of oil and 1,000 kg (2,200 lbs) of a high protein meal remaining after oil extraction (Duke 1983). Studies done in Australia in the 1970's through the 1980's measured rapeseed response to nitrogen fertilization under different irrigation schemes. On a high nitrogen site, Osborne and Batten (1978) found oil yields up to 1,273 kg ha^{-1} (1,130 lbs per acre) under irrigation. Wright et al. (1988) found positive seed yield response to nitrogen fertilization at time of sowing could yield up to 3.8 t ha^{-1} (3,380 lb. per acre) seed, equivalent to approximately 1,500 kg oil per hectare, or 1,300 lbs oil per acre (assuming a 40% oil content). Because rapeseed is more adapted to cooler climates than many of those found in Hawaii, any experimentation with rapeseed would most likely need to be carried out in winter months or at high elevations. In some areas, rainfall may be plentiful enough during winter months to grow rapeseed un-irrigated. Rapeseed can be grown in rotation with grains, flax, corn, sugar beets or fallow, but it should not be grown after itself, mustard, or sunflowers (Duke 1983).

3.4 Sunflower – *Helianthus annuus*

Sunflower is an annual, upright, broadleaf plant with a growing cycle of approximately four months from planting to maturity. It is native to the western United States, and it was spread throughout North America by Native Americans. The seeds are harvested for edible oil production, commercial birdseed, and as a snack-food for human consumption. Production of sunflower takes place all over the world, including western Russia, Ukraine, and Argentina. At one point, sunflower was the primary crop for vegetable oil production behind soybean. The FAO estimates that 27.6 million MT (60.7 billion pounds) of sunflower seed will be harvested worldwide during the 2005/2006 season, an increase of 1.7 million MT (3.7 billion lbs) from the season previous (FAO, 2005).

Sunflower field

Sunflower seeds

Sunflowers require approximately 120 days until maturity, being in full flower for 70-80 of those days (MAFRI, 2004). It is important to grow sunflower in rotation with other crops, as they are highly susceptible to diseases. Sunflower should not be grown in a single location more than once every four growing seasons (Duke, 1983). Nitrogen requirements are high for such a short growing period, in the range of 90 lbs ac^{-1} following a non-leguminous crop or fallow conditions. Sunflower does supply a large volume of biomass along with its seed production, up to 10-12 t ha^{-1} (8,900-10,600 lbs per acre) being possible under favorable conditions.

Sunflower can grow in a wide variety of conditions, but it is considered to be an inefficient user of nutrients. An extensive root system allows the sunflower to be grown in dry areas that will not support many crops. Average yields of approximately 1,500 kg ha^{-1} (1,335 lbs per acre) are lower than soybean yields, and the necessary inputs are greater (Pimentel and Patzek, 2005). The oil content of sunflower seeds ranges from 25-45%, depending on the variety grown. Insect, fungal, and viral pests can have detrimental effects on sunflower yields. The crop was tried in Hawaii in the 1920's, but the trials were considered to be unsuccessful (Roecklein et al. 1982).

A major problem with sunflower production in Hawaii is the prevalence of birds that will consume a large portion of the desired seed. Birds will attack the cotyledon leaves of sunflower much as they feed on soybean plants. This activity can virtually destroy entire stands. Local growers who attempt to produce sunflower at a small scale for personal use have continually met with disappointing yields due to bird predation on the seeds (Osgood, 2006). One possible reason for such heavy bird predation is the need to 'dry down' the crop during cool weather, which Hawaii rarely experiences. The longer time to 'dry down' in the field allows for more bird damage. This factor likely makes sunflower unsuitable for proposed use as a biodiesel crop in Hawaii.

3.5 Peanut or groundnut – *Arachis hypogeae*

The peanut is a leguminous, herbaceous annual that is primarily used as an edible crop for consumption by humans in all parts of the world. It is suited to temperate, subtropical, and tropical climates, where the plant can grow up to 2 feet tall or higher. Peanuts are produced in pods underground, with each pod containing between 1 and 5 seeds, although most commercial peanuts are selected to have two seeds within each pod. Most peanuts grown in the U.S. are grown in southeastern states, where the warm climate allows the peanut to thrive. Peanuts are used primarily for human consumption, whether it is through roasting of seeds, or the production of peanut butter or peanut oil. The peanut shells have multiple uses as by-products, such as high-fiber roughage in livestock feed, a fuel source for heating, mulch, and the manufacture of fertilizers (Putnam et al. 1992). Peanut oil was the original oil used in Rudolph Diesel's engine that he designed in the 1890's, although it was later replaced by petroleum-derived fuels.

Peanut plant (soil cut away revealing peanuts)

Peanuts exposed in-shell

Peanuts grow best in fertile, light soils with relatively low amounts of organic matter. The loose, friable nature of such light soils allow for easier harvesting of the seed pods, whereas heavy, thick soils can restrict extraction of the seeds from the subsurface and cause damage to the hull. Before planting, tillage that is similar to that for corn or soybeans is recommended, and they should be grown in seasonal/yearly rotation with other crops. Maturity can be expected to be reached between 100-150 days after planting, although some varieties may mature within 80-90 days under the right conditions.

Oil content of peanuts ranges from 40-55% by volume. Maximum oil content of the peanut is reached 6-7 weeks after pollination and pod formation. Harvesting of peanuts is quite labor- and equipment-intensive, involving a shearing of the taproot approximately 15 cm below the soil surface, followed by removal of the plant and shaking of the roots to loosen soil from the pods. The plants, with pods upturned, are left in the field to dry for 2-3 days, at which point they are combined with a thresher that separates the pods from the root mass of the plant, and leaves the remaining plant matter on the surface to be tilled under the surface as a source of fertilizer and organic matter. In 2002, peanut farms had the highest energy expenditure for production with a rate of $0.15 per dollar of output (Miranowski, 2005). There is some history of peanut production in the Hawaiian Islands. They were produced in Hawaii as early as the 1830's, but never on a large scale. The Hawaii Agriculture Experiment Station implemented studies in 1902 and 1908, and made recommendations on suitable practices for cultivation of the peanut on a commercial scale (Crawford, 1937). Conclusions made from the study begun in 1908 stated that the size of nuts produced had increased significantly over the size of the seeds used for establishment some three years prior (Krauss, 1911). It was noted at that time that Hawaiian soils were well-suited to peanut production, and the warm climate could result in high yields.

As with many crops, peanuts could have two potential harvests during one year's time in Hawaiian climates. Krauss (1911) reported yields for five different varieties ranging between 1,728-2,249 lbs ac^{-1} (1,940-2,520 kg per hectare) in trials conducted from 1908-1910. Work done at the University of Hawaii in the 1960's on *Arachis hypogeae* showed yields of 1.12 lbs 40 $ft^{2\ -1}$ (Eastman, 1963). This converts into approximately 1,220 lbs ac^{-1}, but the extrapolation of the data is far from conclusive, as such small field trials generally do not give an accurate picture of true potential yields. Other work was done with peanuts at UH during the 1960's, but all of it was conducted in pot trials, which only tested soil types in relation to peanut productivity (Eastman, 1963; Oya, 1964). These trials provided information on possible soils that could be used for peanut production in Hawaii, but their applicability to actual yields leaves much to be desired. There are still small-scale operators growing peanuts for local consumption within the Hawaiian Islands, and peanuts could be expected to produce well here, as long as they are grown in rotation with other crops. Peanuts can attract birds at harvest, but because the shelled peanuts are only exposed for a short period of time the birds are less likely to find the fields early enough to feed heavily on the nuts. Some losses can be expected to occur.

3.6 Palm oil (Palmaceae) – *Elaeis guineensis*

Palm oil is derived from the fruit (both the flesh and the seed) of a tall palm species that can grow up to 20m (over 65 feet) tall. The trunk is a ringed, erect, heavy trunk, and the foliage is in the form of pinnate blades that may number up to 150 per frond (Duke, 1983). The fruits from which the palm and palm kernel oil are extracted grow in bunches in upper reaches of the tree. The fruits are produced in large clusters numbering from 200-300 per cluster, weighing up to 20 pounds. Each fruit is about the size of a plum, and the oil content of the fleshy endosperm can be anywhere from 40-70% in some varieties, and palm kernel oil contents are typically about 50%. The oil palm originated along the western coast of Africa, and has since spread to most tropical areas in the world. Palm oil is used as an ingredient in margarines, vegetable oils, candles, lubricants, soaps, and more recently, biodiesel production. The oil cake by-product is used as livestock feed in many countries (Roecklein, et al. 1982). The majority of palm oil produced around the world is concentrated in Malaysia, Indonesia, and Africa.

Elaeis guineensis occurs in the wild in freshwater swamps and in forests with meandering and braided river channels. It will tolerate periodical water-logging or flooding (such that may occur along riverbeds). As long as an adequate water supply is readily available, the oil palm should survive well. Extremely rocky, sandy, or peaty soils, as well as soils that remain waterlogged for long periods of time, should be avoided when attempting to establish a stand of oil palm trees. It may take up to 8 years for leaves to show signs of full senescence, and even longer for the first fruiting cycle to take place. Propagation can be arduous, and it may take 18 months before seedlings can be transplanted from growing media to field locations. In selected varieties of Malaysia, fruiting is reported to begin as early as 2.5 years after planting, and trees are usually grown for 25-30 years until replanting, due to the difficulties in harvesting from large trees (Wahid et al., 2004).

Mature oil palm

Cluster of oil palm seeds

The African oil palm requires adequate light and moisture, and it is slightly hardier than coconut, although it does not tolerate as high of levels of salinity as coconut. Coastal alluviums are desirable for cropping this tree, with relatively flat topography aiding greatly in any harvesting operations. In areas receiving approximately 2m of annual rainfall, the oil palm can survive without any significant supplemental irrigation. This rainfall should be evenly distributed throughout the year for best results. Constant sunshine on the order of about 5 hours per day is necessary during all months of the year to maximize bunch production (Hartley, 1967). A short drought period of approximately three months will still give oil yields comparable to many other oil crops, but to maximize oil production the above guidelines should be followed (Hartley, 1967). Hartley also notes that successful production of oil palm has taken place in many parts of the tropical world that do not have perfectly ideal conditions, such as evenly-distributed year-round rainfall, low temperatures persist in certain months, or sunshine hours are lower than recommended.

The Malaysian Palm Oil Board (MPOB) has done extensive work with agronomics, physiology, breeding, genetic engineering, and processing of oil palm. From work conducted within their programs, recommendations for siting and cultivating oil palm may be adapted. Key to palm production is canopy closure. The earlier the canopy of palms can close out the understory, the greater the yield response will be. Solar radiation and soil moisture are two critical factors in palm development, and atmospheric humidity can have a very strong influence on photosynthetic capacity by affecting stomatal opening and CO_2 uptake (Wahid et al., 2004). This information allows for greater confidence in selecting sites for establishment of new plantations. MPOB also has information regarding specific fertilization measures to ensure continuous fruiting and proper crop maintenance on a large-scale. Other palm oil breeding and research operations are in place throughout the world, including CIRAD in developing nations and IOPRI, the Indonesian Oil Palm Research Institute.

Once sites have been isolated for production and starter trees have been propagated, plantation layout must be determined. In most areas where the African oil palm is cultivated commercially, tree spacing is approximately 9m x 9m, thus a 50,000 tree plantation would require over 400 hectares (1,000 acres). This spacing would give canopy closure within 5-6 years, and it would give nearly complete photosynthetically-active radiation interception near

100% (Wahid et al., 2004). If each tree were to average five bunches of fruit per year, with each bunch yielding 1 kg of oil, then approximately 250,000 kg (550,000 lbs) of oil would be produced annually (Duke 1983). A highly-developed breeding and selection program would isolate and develop high-yielding varieties capable of such production.

One hectare of trees could produce 5,000 kg of oil, or almost 6,000 liters of oil, by conservative estimates, which could produce almost 4,800 liters of biodiesel (Journey to Forever, 2006). It has been stated that palm oil can have high levels of fatty acids, which require extra methanol transesterification before it can be used as biodiesel, thus increasing the cost of production somewhat (Crabbe, et al. 2001). As of 2002, it was advised that wide-scale production of biodiesel, in particular from palm oil, was not feasible economically because of its high cost of production (Kalam and Masjuki, 2002). Malaysia is the largest producer of oil palm in the world, supplying over 8.5 million tones per year (Husain, et al. 2002). Malaysia's access to ideal growing conditions and inexpensive labor has allowed it to drive the world markets for palm oil. Commercial yields in Malaysia range from 6.5-7.5 tonnes oil ha^{-1} $year^{-1}$(5,800-6,700 lbs ac^{-1} $year^{-1}$), and experimental and theoretical yields range from 10-12 tonnes oil ha^{-1} $year^{-1}$ (8,900-10,600 lbs ac^{-1} yr^{-1}) (Wahid et al., 2004).

The atmosphere for production has changed dramatically since 2002, and the decreasing production costs from improved technology should continue to push the development of biodiesel. One of the primary concerns of production of the African oil palm is the harvesting technique. Whereas many developing nations have a plentitude of labor available to hand-harvest bunches high atop the trees, Hawaii would have to rely on mechanized harvesting operations. A set of mobile lifts could be engineered to drive along the tree lines with workers cutting bunches from a 'crow's nest', similar to cherry-pickers used in harvesting some fruits of taller-growing produce trees around the world. Another potential answer to the issue of costly harvesting is the use of dwarf varieties of oil palm. Yields are not as high as the standard oil palm, but the comparative ease of operations may be able to offset yield losses.

Because oil palms are tree crops, the necessary spacing of a plantation layout for such crops dictates that large areas would be available for intercropping with some small perennial or annual crop. With 30 feet or more of space in inter-row areas, sufficient space would be available to produce crops such as taro (dry land), produce (asparagus, greens, tomatoes, etc.), or specialty nursery-type products such as flowers and ornamental plants. Aside from the by-product market development from the remaining products after oil extraction from the oil palms, this inter-cropping system would supply an alternate stream of income for any lands dedicated to an oil palm plantation. It would also be possible to grow another type of oilseed-bearing crop within the rows of a large oil palm planting.

A factor for consideration in selecting crops for biodiesel production should be the knowledge-base that currently exists for a particular crop. Oil palm has been heavily researched for production capabilities, breeding and genetic improvement, and by-product utilization. The MPOB has discovered that tissue culture is the most efficient and effective way to rapidly multiply uniform planting materials with desired characteristics. By crossing with indigenous African varieties and other species of oil palms found in the Americas (*Elaeis oleifera*), the MPOB has been able to breed slower vegetative growth, increased bunching, high oil contents, and insect and disease resistance into their commercial varieties of oil *Elaeis guineensis* (Wahid et al., 2004). Another benefit of MPOB's crossing with the Central and South American species of oil palms is that they have developed hybrids that perform well in slightly drier climates, a trait that would permit more flexibility in the use of oil palm in Hawaii.

The establishment costs can be high, the period to wait until potential harvest of fruits is longer than most oil crops, the cost of labor for harvest will grow each year due to increased difficulty in operations, and the guarantee of heavy fruiting is not present when it comes to commercial production of palm oil specifically for biodiesel. Even with all these potential concerns, the African oil palm is the highest oil-producing oilseed crop or tree available around the world. Because of the potential for high returns, *Elaeis guineensis* should be considered for small field testing in ideal climatic settings in Hawaii to determine its long-range potential for supplying biodiesel. Breeding and selection procedures carried out by foreign research groups have isolated high-yielding varieties with ideal growth characteristics. If pursuit of oil palm in Hawaii is to be undertaken, efforts should be made to bring in advanced germplasm from several locations.

3.7 Kukui tree – *Aleurites moluccana*

The kukui tree can grow up to 20m in height, and has an ornamental, widespread branching system where flowers and, subsequently, nuts are produced. The nuts can have oil contents ranging from 45-65%, and this high oil content is likely behind the common name of the kukui tree: the candlenut tree. Native Pacific islanders once used the nuts themselves as torches and candles, simply lighting them on fire and using them for light until the oils would burn out. Oftentimes, the nuts would be strung together and lit to be used as timekeepers in local villages. The kukui tree is native to Pacific islands and Southeast Asia, and has been utilized by indigenous peoples for thousands of years. Uses for the nut, specifically its extractable oils, include quick-drying waterproof oils for boats and paper, soap making, illumination, fertilizers from the remaining press cake, and as protection from insect damage. The kukui tree is grown throughout tropical latitudes around the world, but no large-scale production takes place. Most kukui trees are utilized for their nuts, but typically only in small quantities by small craft artisans, as the nuts when strung together make highly desired necklaces.

Kukui (candlenut) tree

Kukui leaves and nut

Kukui trees grow in most tropical and subtropical settings up to an elevation of about 4,000 feet. They can thrive in moist or dry climates, but they do not tolerate hard freezes that last for more than a few days. The kukui tree is spread all over the Hawaiian Islands, but is not cultivated in any organized production scheme. If commercial production were to be pursued, plantings of 300 trees ha^{-1} (120 trees per acre) would be appropriate. One tree is capable of potentially producing 35-45 kg (75-100 lbs) of nuts per year (Roecklein, et al. 1982), yielding approximately 3,000 kg of oil per hectare per year (2,650 lbs oil per acre per year) (Duke, 1983). Other estimates put the potential yield for kukui nut oil from 1,630 to 1,840 kg of oil per hectare (1,450 to 1,630 lbs per acre) based off spacing for 175 trees per acre (Dudley, 2006). Estimates made by the Hawaii Agriculture Experiment Station in 1913 put potential production of kukui nut oil at over 2.3 million gallons of potentially extractable oil from the estimated 15,000 acres of mountain land occupied by kukui trees. As of the mid-1980's, it was estimated that only about 100 acres of seven-year old kukui trees could replace all wild-collected nuts that were currently being harvested in Hawaii (approximately 500,000 pounds per year) (Dudley, 2006).

Early collection methods of kukui nuts would have been primitive and the widespread distribution of harvestable stocks of nuts would be serious setbacks to any type of harvest. If grown in plantation settings, this tree would still present significant problems for harvesting and processing of nuts for oil. The trees would need to be managed to flower and drop the fruits in a near-simultaneous manner in order to facilitate orderly harvesting operations. The harvesting would have to be conducted with some type of vacuum system that could quickly collect fallen fruits from around the trees. To make the operation as efficient as possible, the harvesting machine could also pass the nuts through a de-corticator that would remove the husk and 'meat' from the nut, separating those parts from the oil-bearing seeds. This process may prove difficult, as kukui nuts are renowned for their hard outer husks. The kernels are also difficult to separate from the sides of the shell (Duke, 1983). If grown as a tree crop in long rows, kukui nuts could also be harvested similarly to macadamia nuts. A system of nets could be strung up below the trees to serve as catchments for the falling nuts. Harvesting operations could then move along rows in regular rounds, extracting the nuts from the nets by unfastening or lowering one end.

The kukui tree is grown for commercial uses in Sri Lanka and other Southeast Asian nations where costs of living have remained low and labor can be cheaply secured. In Hawaii, annual exports of kukui nut oil reached a maximum of about 10,000 gal yr^{-1} (37,850 liters per year) in the mid-1800's (Crawford, 1937). The current kukui oil market in Hawaii imports most of its nuts for processing from other tropical nations. The labor in those other locations allows nuts to be harvested cheaply and shipped to be processed in other locations. The kukui nut oil extracted currently around the world is used for cosmetics, making it more lucrative for this purpose than it would be to grow kukui for biodiesel production.

Kukui is an attractive alternative fuel source because it is indigenous to Hawaii. Plantation-style plantings of kukui trees would be easily-associated with Hawaii if they were to be undertaken as a serious replacement for petroleum diesel. Acceptance by the community also would make kukui ideal for adoption of a biodiesel program. Unfortunately, kukui trees consume large areas of land, and they are not expected to respond well to any sort of 'hedging' practice to control their shape and harvestability. The value of the nuts' oil as a cosmetic product also greatly diminishes the interest of would-be growers to produce the nuts for fuel. It is unlikely that kukui plantings would be an efficient use of the land and labor available in Hawaii presently.

3.8 Avocado – *Persea americana*

Avocado is a fruit which originated in Central America. It is an upright-growing evergreen that can reach up to 20 m in height. The tree may have up to a million flowering buds in one growth cycle, but less than a tenth of one percent of those will produce fruit. The fruit is oblong, or pear-shaped, and has a fleshy fruit that is consumed as produce. Each avocado has a large seed inside of the edible, fleshy fruit. The avocado flesh can have oil contents ranging from 10-30% based on variety, and avocado oil is extracted from this portion for use in cosmetics mostly (Roecklein, et al. 1982). Avocados were historically a 'backyard crop', grown in people's yards for personal consumption. Many avocados today go unused and are allowed to decompose on the soil surface in many parts of the world. Commercial production of avocados takes place throughout Mexico, Central America, the Caribbean, the Mediterranean, and in the U.S. in Florida and California primarily, with minor production in Hawaii of 740,000 lbs (336,000 kg) in 2004 (HASS, 2005).

Tall, mature avocado tree

Ripe avocado, cross-sectioned

Avocados are well-suited for a variety of growing conditions, as long as no periods of prolonged cool weather threaten them. The Mexican varieties are the hardiest, and they can withstand temperatures down to -4ºC; the Mexican varieties also have the highest oil content in the fleshy parts. No significant work has been done with avocado seeds, although they are believed to be toxic to rodents, and their oil contents have gone unreported (Duke, 1983). The tree can be grown under a variety of conditions and soil types, including clays, sandy soils, and volcanic loams. Avocados will grow in slightly alkaline to slightly acidic soils, but they will not tolerate poorly-drained or waterlogged sites. Yields in California and Florida were 2.82 and 4.38 tons per acre, respectively, in 2004, whereas in Hawaii, yields were only 1.37 tons per acre for the year (HASS, 2005). Spacing is very important in the successful production of avocados, as the branches will die back if they come into contact with one another. This feature forces low-density plantings of avocado trees, making for what may be inefficient use of lands for maximum oil crop production.

Avocado production in Hawaii has been steadily increasing over the last few decades. In the 1910's the potential for spreading of the Mediterranean fruit fly forced Hawaiian production out of trade with mainland markets. By the time the fruit fly had become established in

California, there were few markets remaining in which Hawaiian producers could compete. California and Florida growers expend great amounts of money to market their products, leaving Hawaiian growers to rely on inter-island and foreign demand. The potential for significant production in Hawaii does exist due to favorable growing conditions, but the reality of establishing large areas of avocado production as well as the large-scale harvesting and processing for oil extraction would not be cost-efficient by today's economic standards.

A potential way to utilize avocado for biodiesel production would be to develop a system of collections from avocado growers in which culled fruits are picked up and taken to a centralized facility that could press oils from the flesh mesocarp. Although this would not deliver a highly significant amount of vegetable oil for transesterification, it could be done as part of a sustainable approach to utilize all waste products for biofuels production. This scenario is probably too far-fetched to ever gain traction, but it is the most likely method of developing demand for avocado culls. Because they are grown all over the Islands and they can produce large amounts of fruits (many of which do go to waste), avocados could supplement any well-organized, highly-efficient operation producing significant quantities of biodiesel.

3.9 Coconut – *Cocus nucifera*

The coconut palm is a tall-growing palm variety that can produce a large number of fibrous fruits each year. It can reach heights of about 30 m, with bunches of fruits growing in the upper reaches of the tree. It is believed the coconut palm originated on the northwestern coast of South America, but it is now found in most tropical areas, as well as some temperate areas with at least four consecutive months of above-freezing temperatures. Copra, the dried flesh or meat from the nut is produced around the world for the oil it contains. Coconut oil accounts for nearly 20% of the vegetable oil produced in the world, and copra oil content can range from 60-80%. Coconut oil is used in a wide variety of products, including margarine, baked goods, confectioneries, resins, soaps, candles, and cosmetics. It is grown commercially in many developing nations of Southeast Asia where the demand for exportable crops with multiple uses is high, and the labor to supply those crops is cheap.

Coconut trees along a shoreline

Cluster of immature coconuts

Coconut grows on a wide range of soils, from wet, subtropical areas to dry, tropical zones to wet, tropical forested zones. It can sustain pH's from the low 4's to around 8. Coconuts are propagated from seed, and some varieties may begin yielding fruit in the first 6 years or so. Typically, fruiting will not occur until 8-10 years after germination, and a full crop of fruits should not be expected until 12-15 years after planting. For fully developed copra and highest oil yield, coconuts should be harvested at full ripeness.

The coconut tree will flower and fruit year-round, and one cycle will last 12 months from flower to fruit-set to ripening. A worker may harvest ripe fruit from 25 palms day^{-1} if harvesting by climbing and cutting from individual trees, and up to 250 palms day^{-1} if using knives attached to long bamboo canes used for reaching high up into trees. Average yield is 250 lbs of oil from 1,000 lbs of nuts, with 60-100 nuts per year from a fully productive tree (Duke, 1983). Methods of propagation, harvesting, and processing make coconut a valuable commodity where workers can be afforded at low wages, but the feasibility of implementing large-scale coconut plantings in developed regions is likely not economically feasible. Coconut oil has the potential to yield 50% motor fuel (as diesel fuel), and many useful by-products may be extracted during the process. The fibrous shell can be used for a variety of purposes, the seed cake is an excellent feed supplement for livestock, and residues after oil extraction may have potential for small amounts of ethanol production and glycerin.

There is no significant commercial coconut production currently developed in Hawaii, other than the selling of small amounts at local markets, and the harvesting for personal use. Coconut oil sold in local markets is not produced locally, but it is shipped in from international suppliers. The high cost of labor and land has been a factor in the lack of a developed market in Hawaii for many decades, dating back to the late 1800's and 1900's. These conditions have pushed any significant planned production to be abandoned and implemented in the Philippines, mostly, over the last hundred years. The Philippines have begun research into coconut as a potential biodiesel source, and their initial findings have shown the biodiesel produced to be of high quality for replacement of petroleum fuel sources. There are reservations about the establishment of coconut biodiesel because of lack of public awareness of its potential. It is believed that the use of biodiesel from coconut oil would solidify the Philippines' position as the leading coconut producing nation in the world, and it could increase profits for the growers involved in other means of coconut production (BAR, 2005).

Coconut oil is unusual from many vegetable oils in that it remains solid at relatively high temperatures. When in liquid form, coconut oil burns very cleanly in diesel systems, especially in a B20. In order to address this problem in nations where coconut oil is readily available, especially in the South Pacific, fuel systems have been adapted to start using petroleum diesel, switch over to coconut oil while running, and before shut-off, switching back to regular diesel fuel. This keeps the engine from clogging with the easily-solidified coconut oil, while still running mostly on the cleaner fuel (Cloin, 2005).

Hawaii has the potential to support large areas of coconut trees for the purposes of oil production. Coastal areas that have not been developed could be used to produce fuels for the Islands because of the coconut palm's tolerance to salinity in the soil. Coconut palms can take hold in any coastal environment when allowed to do so. Harvesting would be an almost continuous process, providing jobs for those in rural coastal areas. The processing of the fruits would be the most time-consuming and difficult part of coconut production for biodiesel. Because coconuts are relatively tough nuts, the extraction of the meal and oils can be arduous, and this extra cost in processing is something that would discourage most landholders who may be in a position to consider utilizing coconut palms.

3.10 Jatropha – *Jatropha curcas*

Jatropha curcas is a small tree that is indigenous to the Caribbean, but it is used around the world in Central and South America, India, Africa, and Southeast Asia to provide natural hedges and fence-rows, as it is not browsed by most livestock. Jatropha trees produce many small seeds that are very rich with oils, containing from 43-59% oil (Gübitz, et al. 1999). The Jatropha seed is considered to be toxic to animals, one of the reasons it is used as a natural hedge in developing nations. It has been estimated that one hectare of Jatropha trees could produce between 1,600-2,000 liters of oil, which can be used for soap-making, various medical treatments, and production of diesel fuel. The Jatropha tree is deciduous, and it grows more like a shrub, growing to only about 5m in height with spreading, stubby branches, losing their leaves in the dry season. The jatropha tree is grown throughout many parts of India, Africa, and Mali, and much of the recent research done into it as an oil seed crop has originated in those regions.

Jatropha trees will grow under a variety of conditions, withstanding high temperatures, drought, slope, and varied pH levels. Most data comes from Jatropha production in regions where water is either too scarce or too expensive with which to irrigate. Little is known about its response to increased water availability. The rooting system is composed of 3 or 4 primary lateral roots spreading near the soil surface and one vertical root that can reach down more than 5 m, allowing it to survive in very dry climates. Jatropha has shown high demands for nitrogen and phosphorous, and fruit maturation takes approximately 45 days, or until the fruit turns a yellowish color (Foidl, et al. 1996). The demands for nitrogen and phosphorous can be easily met, as jatropha is highly efficient at adsorbing nutrients from marginal soils. Using old sugarcane or pineapple lands would aid in lowering fertilization costs because soils in those areas are highly productive, and jatropha can thrive on productive soils. Old pineapple lands may have very acidic soils, but jatropha should be adaptable to those conditions.

Rows of Jatropha trees

Nut cluster and split nuts from Jatropha tree

Seeds are typically harvested by hand, but it is thought that seeds could be harvested using machinery somewhat similar to equipment used for thrashing coffee plants to knock coffee beans loose. Propagation of Jatropha can be done by seed or by cuttings, with trees grown from seed producing harvestable seed crops within two years and trees grown from cuttings producing harvestable seed in the first year of growth. Many uses have been proposed for various parts of the Jatropha tree, such as medicinal uses for the leaves, latex, seed oil, green manure and biogas production from fruit hulls, and fertilizer and biogas production from the seed cake remaining after oil extraction (Gübitz, et al. 1999).

Jatropha trees have never been grown commercially in the Hawaiian Islands, but their suitability for marginal land, and high potential output of oil seed make them an option worth exploring further. The ability of Jatropha plants to grow in somewhat harsher conditions than many oil seed crops would allow prime farmland to be maintained for food production while other agricultural lands could be converted into production of oil crops. The potential for mechanical harvesting is another quality that is not found with larger growing oil seed tree crops. Jatropha will require mechanical harvesting to be economically feasible, and it is believed that harvesters similar to those used for coffee could be designed for use.

The full potential for jatropha is far from being realized, and the growing and management of the trees are poorly documented, with little experience in marketing its products having taken place around the world (Openshaw, 2000). Various parts of the plant have medicinal values, flowers attract bees, making it a viable source for honey production, oil residues from the seed can be used for soap production in the cosmetics industry, and aside from supplying oils for diesel replacement, the growing of the tree itself is effective in reducing CO_2 concentrations in the atmosphere. Jatropha is also a species listed within the Kyoto Protocol as eligible to trade carbon credits, on the order of 8 kg CO_2 absorbed per year per tree capable of being converted into Carbon Credit Certificates that may be traded with other emitters of greenhouse gases as another source of revenue for producers (Openshaw, 2000).

Jatropha will act as a deciduous tree with one fruiting cycle per year when grown without irrigation, but if ample water is made available to the tree on a year-round basis, up to three fruiting cycles may occur within a year. Jatropha can be maintained as a hedgerow by implementing thinning and trimming operations each year (USAID/WSU, 2002). Any trimmed or culled tree parts can also serve as an alternate fuel source, and leftover seedcake after oil extraction makes an excellent organic fertilizer, with N, P, and K (6%, 3%, and 1%, respectively), contents similar to that of chicken manure (Openshaw, 2000). This fertilizer can be used within the farm to help supplement the regular fertilization needed. Because of the toxic properties of the compounds in jatropha, the seedcake may have nematicidal or other pest control properties, while still supplying necessary nutrients for the plants to which it is applied.

Because jatropha could potentially have three flowering cycles within one year, possibilities for large volumes of alternative products are significant. They flower heavily in response to rainfall or irrigation, and bees could have pollen sources for honey production practically year-round. With a healthy growth rate and sufficient rainfall and fertilization, it may also be possible to extract latex and other oils from the plant that have medicinal, pesticidal, and molluskicidal properties (Openshaw, 2000). The leaves of jatropha can be quite large and may serve as a feedstock for silkworms. If non-toxic varieties are used (a variety is said to exist in Mexico and Nicaragua that does not contain the purgative, toxic substance curcin), then the remaining seedcake could be used as an animal feed, as well as the organic fertilizer mentioned previously.

If jatropha is grown in hedgerow-type plantings, annual produce crops could conceivably be grown in inter-row areas of the farm (USAID/WSU, 2002). It may not be economical to carry out such work, unless row spacing was on the scale of over 5 m between each row. In small plantings done at a community scale, this would be a more likely option, but in large plantings, this would be very costly and labor-intensive. Nitrogen-fixing groundcover may be a more viable option in such a scenario, reducing needed applications of fertilizer.

Jatropha has been grown successfully in many tropical and subtropical countries for the purposes of erosion control, improving working and earning conditions for women, and producing fuel that can be used for local needs in developing nations. It is expected that there would not be any significant problems with the establishment, propagation, or processing of oil of Jatropha in Hawaii. The potential of Jatropha for biodiesel production in Hawaii should be considered, and studies to determine its growth patterns would give a better idea as to its feasibility as part of the solution for the transition away from petroleum-based fuel supplies. Currently, there is work underway to install test trials on Maui, Kauai, and Oahu of jatropha utilizing a Hawaii Farm Bureau grant. Tests will involve spacing variances and fertilization and irrigation requirements for initiating a stand of jatropha in hedgerow-style plantings. Jatropha experimentation is also being pursued by HARC staff in conjunction with other private entities interested in developing biofuels for military consumption. Many agronomists in Hawaii feel jatropha may be the most easily-established and efficiently-productive oilseed crop available for immediate research (Osgood, 2006; Uehara, 2006).

3.11 Neem tree - *Azadirachta indica*

The neem tree is an evergreen tree of the mahogany family that is native to India and Burma. It is found in tropical and subtropical climates, withstanding extremely dry conditions, but also tolerating sub-humid conditions. Neem trees are fast-growing and can grow up to 35 m tall, and although evergreen, they will lose their leaves in times of severe drought. They have wide spreading branches creating a scenic, round to oval crown that sits upon a relatively short trunk. One tree can produce millions of flowers, and in one flowering cycle, a mature tree may produce many thousands of seeds. Seeds are small and round to oval in shape, with oil content ranging from 20-33%, depending on the variety (Kaura, et al. 1998).

Neem trees are considered to be a sacred tree in India because of their multitudinous uses. Products derived from the neem tree include neem oils, bark, leaves, and seed cake, each of which can serve a different purpose. In India, neem oil extracted from seeds is used for soap primarily, but it is also used in medicine and as a natural pesticide, capable of repelling various harmful insects from food and fiber crops. Bark is used for tanning due to its high tannin content. Neem leaves are used for their insect repellent properties when crushed and mixed into a spray, and they may also be used as a fertilizer (in rice) or as a mulch. The leftover seed cake from oil extraction makes a good fertilizer that is sometimes used for animal fodder (Neem Foundation, 2005). The wood may be used for heating, construction, and furniture and craft-making, as it is a very dense wood from the mahogany family of trees. Extensive production of neem products takes place mostly in India, southeastern Asian countries, and in small amounts in other tropical and subtropical nations and areas. Some limited production currently takes place in Hawaii.

Neem tree

Branches with neem fruits

Neem can be grown under some of the most extreme conditions imaginable. It will tolerate temperatures up 45ºC and will grow in areas receiving less than 15 inches of rain yr^{-1}. Neem does not tolerate freezing conditions, especially in early stages of growth. Neem will grow in high pH soils up to 8.5, and will work at decreasing the acidity of soils towards a neutral state by a process called calcium mining. The tree can extract calcium from deep in the soil profile, and this calcium is cycled through the tree and returned to the soil as litter, thus regulating pH similarly to adding agricultural lime. Neem can be grown on very marginal soils that may be very rocky, shallow, dry, or pan-forming. Because of its ability to grow on and improve these types of soil, neem production in Hawaii would not need to occupy prime agricultural land. There is a neem variety collection in place at HARC's Kunia substation.

Potential rate of growth and seed production for neem trees are high, but the methods of analysis in place around the world do not give a clear picture of how much growth and output can be expected. Neem trees can start producing harvestable seed within 3-5 years, and full production may be reached in 10 years, lasting until the tree dies, which may be up to 150-200 years of age. It is estimated that a mature neem tree may produce 30-50 kg of fruit each year. One drawback to neem is the collection of viable seeds for oil extraction, and the efficiency at which the oil may be extracted. Another disadvantage of neem is its invasive tendency that is accentuated by the eating of seeds by birds and their subsequent spreading of those seeds (Dudley, 2006). An advantage to neem is its multiple by-products that can be obtained from other parts of the plant, and their potentially high value. The neem tree is almost completely usable in one form or another.

With the growing awareness of the neem tree and its many uses around the world, some data is available as to its potential for growth in Hawaii. In 1991 in Hawaii, a neem tree that had been planted some seven years prior was over 10 m tall and fruiting heavily, and in 1989 the Hawaii State Senate declared neem a 'wonder-tree' that needed more supporting research and development (NRC, 1992). In locations in India, neem oil has been found to yield 50% of the weight of kernel. The oil does have sulfurous compounds, unlike most vegetable oils, giving it a pungent odor and a less-clean burn than other vegetable oils. If the intention of production of biodiesel is to become import independent *and* lessen emissions from fuel-burning, neem oil is not a desirable option.

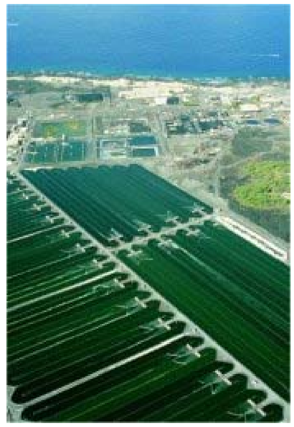
3.12 Algae

Microalgae are some of the most efficient fixers of carbon dioxide (CO_2) on the planet. Their ability to sequester, or trap, CO_2 provoked extensive research by the National Renewable Energy Laboratory (NREL) in Colorado from the 1970's into the 1990's. The work done at NREL was primarily to use algae in containment ponds adjacent to fossil fuel burning power plants to aide in emissions reduction. NREL scientists found that open ponds of algae could sequester nearly all of the CO_2 emitted from those plants, if the residual gases were passed directly into the ponds from below the surface of the ponds. It is estimated that over 100,000 species of photosynthetic microbes exist in nature, and only a small fraction have been identified for potential use on an industrial scale (Sheehan, et al. 1998).

It was known prior to these experiments that certain species of algae, especially those in families of 'diatoms' and 'green algae', are also very high in lipids, or fats. These lipids are the same as many of the oils that are currently extracted from vegetable sources (soybean, rapeseed) for biodiesel production around the world. Different species of algae may contain anywhere from 10-85% lipids, but the slightest contamination of a holding pond can greatly alter expected oil yields, thus decreasing efficiency and profits (Raleigh, 2006). Algae are native to many different habitats around the world, and choosing species for mass production is simply a matter of evaluating native populations for the highest oil-producing varieties. Algae are very good at utilizing sewage wastewater, water with high salinity, agricultural wastewater, and waste streams from fossil fuel power plants, as mentioned above.

By-products from using algae as a source for biodiesel would be the remaining biomass of plant residues (which has approximately the same BTU value as bituminous coal) for burning as an energy source, or use of the remaining plant residues as feed stocks for fish or livestock, due to their high-quality proteins. The production of biodiesel from the oils after transesterification leaves behind a glycerol, which could be used for soap production, similar to other methods of biodiesel production from vegetable oils. It is estimated that under ideal conditions in Hawaii, with pure stock of algae being produced, there would be nearly 450 usable tons of biomass ha^{-1} (400,000 lbs per acre) of algae ponds. This biomass could also be used for other fuel production purposes, such as methane production through anaerobic respiration, and further processing into methanol and/or ethanol (Raleigh, 2006).

Algae are some of the most intriguing options for biodiesel production in America and in Hawaii. Whereas many oilseed crops will take significant amounts of land currently being used for production of food commodities, algae ponds could be located on marginal lands and would not use any further freshwater resources. They could be located in the drier, hotter areas of the islands, where sunlight is plentiful, ocean water is readily available for pumping, and agricultural production is not as prevalent due to high irrigation costs. Algal ponds could also be located directly adjacent to existing fossil fuel burning power plants to capitalize on excess CO_2 streams for uptake by the photosynthesizing organisms. A Cambridge, MA, based company called GreenFuel Technologies Inc., have estimated that a 1,000-megawatt producing power plant, using a several hundred hectare-size algal pond farm could produce more than 40 million gallons (150 million liters) of biodiesel and 50 million gallons (190 million gallons) of ethanol in one year (Hamilton, 2006).



Algae ponds at Cyanotech
Big Island

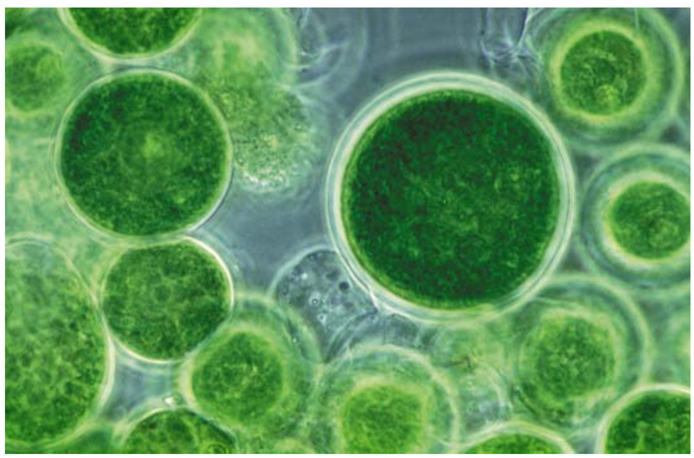
The costs of implementing such pond farms is the greatest obstacle to algae production of biodiesel, especially in Hawaii, where land costs have risen dramatically over the last 20 years. Land that would be suitable for such ponds is often located along oceanfront acreage, which is not necessarily suitable for agricultural production, but development of suburban and luxury housing may keep alternative energy investors out of the market in the short- and long-term. Because of such high land costs, the primary and secondary products must be of high value to ensure profitability (Kadam, 2006).

Hawaii played a role in the work conducted by NREL in the 1980's and 1990's, and algae production continues to be undertaken and researched on the islands. The initial startup for the work done by NREL was to construct 1 ha (2.47 ac) size ponds near Roswell, NM to evaluate production potentials of algal strains. Before they could develop the NM ponds, they instituted ponds in California and Hawaii to test the feasibility of the 'open-raceway'-style ponds. The ponds consist of what appears to be a track, or raceway, in which water is moved around by a small paddle-wheel to keep a measure of turbulence in the system. CO_2 can be injected into the system to accelerate cell growth and division of the algae prior to its harvest for oil extraction. The prototypes in California and Hawaii proved successful, but the style implemented in California (different from the one used in Hawaii) was used for the Roswell trials.

Hawaii Island-based Cyanotech currently raises *Spirulina sp.* for the health foods industry, which is a very high-value product that allows for investment in the necessary land and research to maintain a profitable business. Research is also conducted at the University of Hawaii-Manoa into different strains of algae to be used for various purposes. The University of Hawaii was charged with maintaining stocks of the many isolated species of algae that were used in NREL's research. The algae library's status is defunct at this time, but it is believed that most varieties would have to be isolated and reproduced again for production to restart, as most strains are believed to have been lost over the last decade (Tyson, 2006).

Primary concerns to the efficient production of biodiesel from microalgae were not really limited by engineering constraints, but many of the cultivation issues, including species control in outdoor systems, harvesting and oil accumulation, and overall productivity, are what make large-scale commercial and industrial production impossible at present (Sheehan, et al. 1998; Benemann, 2006). At this point in time, much of the use of microalgae in experimental applications is as a means of greenhouse gas abatement. As mentioned above, microalgae ponds can be used for funneling flue gas rich in CO_2 through, instead of allowing such gases to escape into the atmosphere. By utilizing this quality of microalgae, there will be more opportunity in the future to concentrate research efforts in the capabilities that microalgae can play in efforts to reduce the concentration of greenhouse gases through mitigation policies and utilization of potential by-products for energy and liquid fuels (Benemann, 2006).

One possible way to control some of the events that could lead to a collapse of a microalgae system of biodiesel production would be to utilize closed photo-bioreactors. The use of photo-bioreactors for purposes of inoculum production has been known and practiced for over 50 years (Benemann, 2006). A privately-funded study was conducted in Hawaii that sought to correct the issues of contamination in the raceway-pond system of microalgae production (Huntley & Redalge, 2006). This $20 million study focused on isolating *Haematococcus fluvialis* for production of astaxanthin, a valuable carotenoid pigment. The processes developed in this study proved effective at the scale of operation undertaken (Huntley & Redalge, 2006).



Haematococcus fluvialis' under microscope

For further details into potential uses of microalgae and the engineering specifics, readers are asked to consult the Sheehan, et al. (1998), and Huntley & Redalge (2006) articles cited herein. Because of the complexity of such work, a short review such as the one presented here should be considered as a brief summary. Caution has been advised by those with knowledge of the NREL programs from the 1980's and 1990's as to proceeding full scale with such work, and further work would best be pursued by those with knowledge of such plants and practices (Benemann, 2006; Raleigh, 2006). Agronomically speaking, the commercial or industrial production of microalgae is similar to that of any other crop, but the shift away from terrestrial plants would require alternative expertise than would soil-based crop production.

3.13 Other crops

This section gives a series of brief summaries of miscellaneous tree crops that could be used in some capacity for biodiesel production. The plants listed are not discussed in as full detail as the oil crops in previous sections. This listing is merely intended to give other potential alternatives to production of biodiesel. Some of these trees are not currently located in Hawaii, and the importation of such species can be a long, arduous process that makes the introduction of new species less economically viable than working with plants that are already approved for importation and cultivation in the Hawaiian Islands. Other species are classified as weeds in Hawaii, and their propagation in a commercial setting may not be welcomed by many producers. These species are mentioned herein to recognize their potential a sources of oils for biodiesel production. Some of these species are relatively unknown in Hawaiian agriculture, and their further exploration may prove to be of value in the future.

3.13.1 *Euphorbia lathyris* L.

Euphorbia (also called mole plant, caper spurge, petroleum plant, or gopher plant) is a plant native to the Mediterranean that has a history of cultivation for medicinal and ornamental purposes. It has spread along many areas of the east and west coasts of North America, viewed as an invasive species. It gets its nicknames from its ability to repel moles and other underground burrowers that can harm gardens and yards. In the late 1970's a small number of scientists began to study the 'mole plant' as a possible source that could replace petroleum derived transportation fuels, as the hydrocarbon compounds isolated from *Euphorbia lathyris* were found to be very similar in composition to the hydrocarbon substances found in gasoline (Calvin, 1979). Calvin expressed great interest in utilizing *Euphorbia l.* as a petroleum crop because it could be grown on semi-arid lands that other forms of agriculture could not cultivate. This was important because the production of these types of bioenergy crops could have taken advantage of the semi-arid to arid regions of high sunlight and low soil moisture content, while not interfering or competing with the production of food crops that could only be grown in more temperate climatic zones (Benemann, 1979).

Studies were conducted in the early 1980's to attempt to validate the assumptions made by Calvin in earlier writings. One particular study carried out in Arizona attempted to collect a wide array of genetically different varieties from around the world, only to settle on the accumulated varieties which could be collected from northern and southern California. It was concluded that the amount of energy necessary to produce a viable crop of *E. lathyris* was not economical if replacement fuels for petroleum products were sought (Kingsolver, 1982). Their study also found that the plant was not suited to the xeric moisture regime, the plant oils were an irritant to the skin of workers, and that its oil content responded negatively to increased salinity of irrigation water and growing media. In moist areas with no major salinity problems, *Euphorbia l.* may be productive enough to supply some of the islands' fuel needs. This evidence should be a deterrent to continued pursuit of *E. lathyris* as a source of biofuels in arid regions.

Table 2 Potential production of selected tree crops for oilseed

Crop	Oil content	lbs. oil ac^{-1}	US gallons ac^{-1}	Years to production
Oil Palm	**kernel 50%, fruit 40-70%**	**5346#**	**760#**	**3 to 10#**
Kukui	**45-65%**	**2672***	**380***	**6 to 10**
Avocado	**10-30%**	**1980**	**282**	**1 to 3**
Coconut	**60-80%**	**2018**	**287**	**5 to 10**
Jatropha	**43-59%**	**2106†**	**300†**	**2 to 3**
Neem	**33-45%**	**1161‡**	**165‡**	**10**
Pittosporum	**1.3 ml $fruit^{-1}$**	**880***	**125***	**8 to 10?**
Copaifera	**500 ml $tree^{-1}$ yr^{-1}**	**55§**	**8§**	**10+?**
Pongamia	**27-36%**	**3037¶**	**432¶**	**4 to 8^**

Data taken from Journey to Forever, 2006, except where noted below.
Data taken from Wahid et al., 2004.
* Data taken from Duke, 1983.
† Data taken from Gaydou, et al. 1982.
‡ Estimated 40 trees ac^{-1} @ 33% oil content, with 88 lbs seed $tree^{-1}$
§ Assume 60 trees ac^{-1} with 500 ml $tree^{-1}$ yr^{-1}. Data taken from Plowden, 2003.
¶ Data taken from Duke, 1983. Assume 40 trees ac^{-1} @ 27% oil content, with 40 lbs seed $tree^{-1}$
^ May take as little as 3 years if grafting is method of propagation, and up to 10 years by seed.

3.13.2 *Pittosporum resiniferum* - Petroleum nut

A tree native to the elfin forests found in the Philippines, *Pittosporum resiniferum*, or petroleum nut, produces fruits with petroleum-like aromas that have high oil contents. The fruits are used for oil extraction for fuel, illuminating, and, at one time, medicinal purposes by native peoples. The fruit is reported to contain dihydroterpene and heptane, the latter of which is a main component of gasoline. Extraction of oils from fruits of this tree might be less expensive for processing due to the similar nature of compounds found within the nuts and standard gasoline.

The tree can grow up to 30 m tall, and it will begin bearing fruits at less than 10 m in height. A single fruit may have from 5-72 seeds, with each fruit yielding 0.1-3.3 ml (average of 1.3 ml) of oil (Duke, 1983). Petroleum nut is reported to grow at elevations over 500 m, ranging up to almost 2,500 m, and it prefers moist tropical and subtropical forest zones. Estimates of potential oil yields range from 150 ml to 60 l (0.04 to 15.8 gal) of oil per tree, leaving much to be desired in regards to accuracy in actual yields from scientific experimentation. Small plantings of the petroleum tree would prove useful, if only to determine potential growth rates and yields for Hawaiian climates in order to make more reliable predictions.

Table 3 Potential production of herbaceous row crops for oilseed compared to algae

Crop	Oil content	lbs. oil ac^{-1}	US gallons ac^{-1}	Years to production[#]
Soybean	18-20%	335	48	0.35
Flax	35-40%	359	51	0.30
Rape	37-50%	893	127	0.33
Sunflower	25-45%	714	102	0.4
Peanut	40-55%	795	113	0.4
Euphorbia lathyris	40-48%	2300[†]	315[†]	<1
Castor bean	40-50%	1958	278	<1
Algae*	10-85%	~280,000[‡]	40,000[‡]	<1

* Algae would be grown in large raceway ponds along coastal areas.
[#] Plantings can be established and harvested within a 4-8 month period for these crops. *Euphorbia lathyris* has an unknown time of implementation, but it would not be greater than one year. Algae would need only weeks to begin oil production.
Data taken from Journey to Forever, 2006, except:
[†] Taken from Duke, 1983.
[‡] Taken from Hamilton, 2006.

3.13.3 *Copaifera langsdorfii* - Diesel tree

The diesel tree (*Copaifera langsdorfii*) is a tropical tree believed to be native to Brazil, in northern and Amazonian South America. It is most likely only productive in dry to moist climates with temperature ranges from 20º to 30º C where no frosting occurs. This species of tree has been used for centuries by native peoples, by simply tapping into the trunk of the tree and draining out the 'sap', which has a high content of diesel-like hydrocarbons. With no diesel engines in such remote, jungle-like settings, the indigenous peoples typically used the extracted fuel as a moisturizing rub, an expectorant, a cure for skin diseases, and other non-energy purposes (Duke, 1983). The diesel tree's extracted fuel is said to function as a usable fuel when directly injected into standard diesel engines.

Copaifera langsdorfii is an evergreen tree that can grow up to 35 m tall, and to 1 m in diameter, providing a rather large natural storage chamber for accumulated resins/fuels. Cross-sections of the tree show the hydrocarbons collect in thin capillaries which run the length of the trunk. If the drilled holes only collect the hydrocarbons from ruptured capillaries, then it would be possible that if multiple holes were drilled for tapping near the base oil yields could be greater (Calvin, 1980). In the same study, Calvin reported potential yields of 40 l $tree^{-1}$ yr^{-1}, if harvested twice each year from the same plug-hole. Calvin sent harvested samples to Mobil Corporation for analysis of cracking pattern, and it was discovered that the extract made a viable replacement for petroleum-derived diesel fuel. USDA reports potential oil yields of 53 liters (~14 gal) per tree in one year's time (Duke, 1983), and at current diesel prices at the time of this report (~$3.30/gal), one acre of 500 fuel-producing trees could yield approximately 26,500 liters (7,000 gal) of diesel-like fuel in one year's time, worth over $23,000.

Recently, Plowden (2003) has explored *Copaifera* species in the Brazilian Amazon. Plowden sought to determine the economic value of the extracted oleoresin from the trees for the native peoples who inhabit those areas. He found that oleoresin peaked in trees with dbh's (diameter-at-breast-height) of 55-65 cm. The average amount of liquid drained from this size class tree was 459 ml on the first sampling, and the totals decreased with each subsequent sampling. Larger trees had less oleoresin available for extraction than medium-sized trees, and trees with dbh less than 35 cm yielded none of the oleoresin. The trees harvested during the rainy season did have significantly higher amounts of the oleoresin, but none of the trees yielded 1 liter (0.26 gal) in any of the samplings. Plowden's results from the 2003 study dictate that *Copaifera* should probably not be pursued to meet Hawaii's biodiesel needs. It would be of interest to have several trees available to observe for future informational purposes, but its likelihood as an efficient producer of readily extractable oleoresins appears very slim.

3.13.4 *Pongamia pinnata* – Pongam tree

Thought to be native of coastal India and Polynesian areas, the pongam tree has been used for centuries for medicinal purposes, fertilizer, shade, lubrication, minor construction, and illumination. Pongam trees are deciduous, sub-evergreen trees that may grow up to 25 m tall, thriving in areas from sea level up to 1200 m (Duke, 1983). It is reported that pongam trees can tolerate drought, frost, heat, limestone, sand, and salinity, and they will grow under conditions ranging from near 0º C up to over 50º C, annual rainfall up to 2.5 m, and almost any soil type, including areas where roots must persist in salt water. Pongam trees prefer areas with a dry season lasting from 2 to 6 months (World Agroforestry Centre, 2006). These durable qualities would likely make pongam trees well-suited to the varied conditions found across the Hawaiian Islands. The tree was introduced to Hawaii in the 1960's by Hillebrand, and it has also been introduced into parts of southern Florida (World Agroforestry Centre, 2006).

Pongam fruits are reported to have oil contents ranging from 27-36% by weight with a multitude of uses mentioned above. By-products consist of wood for fuel, leftover press cake for poultry feed, leaves as pest repellent in stored feed, and glycerin for soap-making. Trees reach adult height in 4-5 years and may begin bearing seeds in 4-8 years. Trees will regenerate readily by suckers, which spring forth from the buried roots extending from the tree's trunk. This characteristic can make the pongam tree somewhat difficult to manage, as it may cause significant weed problems. Planting of seeds directly into the soil is the standard method of cultivation, but seeds do not open naturally and must decay before germination will occur.

The seedcake remaining after extraction contains small amounts of moderately toxic substances, including karanjin, pongamol, and tannin. The oil is bitter tasting, and the taste and toxic substances limit its use as a supplement to livestock diets. Because of its toxic characteristics, pongam seed cake can be utilized as a nematicide when used as a top-dressing for the soil and dried leaves can be used similarly to neem leaves by crushing them up and mixing them with stored grains to repel damaging insects (World Agroforestry Centre, 2006).

Assuming 100 trees ha^{-1}, yields could range from 9-90 kg seed tree $^{-1}$(20-200 lbs per tree), giving totals of 900-9,000 kg seed ha^{-1} (800-8,000 lbs ac^{-1}). Rates of extraction in India average 24-27% in processing facilities (Duke, 1983), and improved technology and efficiency could be expected to increase yields up to 30-33% extraction by weight. Such improved methods could thus give yields between 2,700-3,000 kg oil ha^{-1} (2,400-2,650 lbs oil ac^{-1}). The directly extracted oil has shown to be a suitable replacement for standard petroleum-derived diesel fuel in engines, showing good thermal efficiency. Pongam trees may warrant exploratory trials to determine if their oils would be suitable substitutes in diesel-powered engines, and to determine potential yields in Hawaiian soils and climate zones, plantings could be undertaken at various locations.

3.13.5 *Moringa oleifera* – Ben-oil tree

The Ben-oil tree is believed to be native to India, Arabia, and possibly even across Africa and the Caribbean. It has been used by tropical societies for centuries as folk remedies, food, living fences, cleaning and disinfecting, lubrication, and cosmetics. The trees are short and slender, rarely growing above 10 m in height, and the seeds are produced in long pods containing about 20 seeds within the pith (Duke, 1983). The Ben-oil tree is found in subtropical to tropical dry to moist climates, tolerating rainfall from 0.5 to 4 m annually with temperatures ranging from 19 to 28°C. These trees are said to tolerate drought, sandy soils, bacteria, and fungi.

Propagated most easily by planting cuttings, Ben-oil trees are capable of producing seed pods within the first year after planting. By the second full year, full fruit bearing can be expected. The trees can continue to produce pods for several years. It is possible to get two complete fruiting cycles within one calendar year, depending on climatic conditions. There is little yield information available to estimate production rates in Hawaii, but it is believed that this tree could produce large amounts of seed for oil extraction. The seeds contain 35-40% non-drying oil, and the remaining seed cake after extraction is reported to be very high in crude protein (nearly 60%), making it a desirable source of animal fodder (Duke, 1983). Oil qualities are similar to that of olive oil, and the degummed oil has favorable characteristics for use as a replacement for petroleum diesel (Tsaknis, et al. 1999). Because very little information exists regarding cultivation of *Moringa oleifera*, it may warrant further exploration via small field trials.

3.13.6 *Ulex europeaus* - Gorse

Gorse is a thorny, woody legume native to western and central Europe and areas adjacent to the Mediterranean Sea. Used in Europe for centuries as a natural hedge for livestock fencing, gorse was first observed on Maui in 1910, and it was originally used to provide hedging for sheep (Haselwood & Motter, 1966). Gorse is well-adapted to thriving on poor quality soils with low fertility and little available water. Gorse infestations can occur because of overgrazing of pasture lands as well. A gorse-infested landscape generally has little floristic diversity, because gorse can out-compete most other plants with its highly efficient use of water and nutrients (Leary, et al. 2006). Infestations on Maui and Big Island have reached epidemic proportions, and gorse is considered to be a noxious weed by the State of Hawaii. Total area of gorse-infested lands on Maui is approximately 2,000 acres, and total area on Big Island is over 5,000 acres (Dudley, 2006).

Gorse is considered a noxious weed in many other states, mostly on the west coast of the mainland, and its control is a necessity in fire-prone areas. Gorse has significant oil content in its woody branches and stems, making it highly flammable. No documentation exists on the amount of oils that could be extracted from harvesting the foliage of the gorse plant. There has been some discussion by landowners on Big Island to cut gorse for purposes of oil extraction in order to utilize the some 5,000-odd acres of infested lands on the southern slopes of Mauna Kea. This infested area, as well as areas on Maui's Haleakala, is hardly suitable for production of other agricultural commodities, as gorse can negatively alter the state of the soil by depleting stocks of calcium, magnesium, manganese, and zinc, four of the essential nutrients for healthy plant growth (Leary, et al. 2006). Gorse can also lower soil pH to moderately acidic levels below 5.0, conditions which will not prove favorable for most agricultural crops. Because of these reasons, gorse could be utilized for some form of biofuels, whether it is for oil extraction or for chopping to use as feedstock for producing electricity, but gorse is not recommended to be purposely propagated in any situation. If landowners with infestations wish to harvest gorse for some form of biofuels, it is up to them to responsibly do so while limiting its spread beyond its currently inhabited areas.

3.13.7 *Ricinus communis* – Castor bean

Castor bean has been used for medicinal purposes for many decades. It also produces highly-useful, fast-drying oil that can be used in industrial applications. The oil has been used for coating fabrics, lubricating machinery, producing printing inks, textile dyeing, and leather preservation. The leftover seedcake (protein-meal) has a highly-toxic component known as ricin, a blood coagulant that can be lethal in very small doses. There are expensive means of detoxifying the seedcake after oil extraction, if the high-protein meal needed to be used as animal feed. The oil can be used in medicinal applications as well, but only in small doses. It produces immunizing activity in the body, producing small doses similar to antitoxins produced naturally by the body to fight against bacteria (Duke, 1983).

The seeds of castor bean have between 40-50% oil content, and the castor bean plant can grow as perennial in tropical climates. The plant can grow up to 10 m in height, and when seeds are fully ripe, they are often shot from their pods atop the plant (Haselwood & Motter, 1966). This means of releasing seed, up to 25' in some instances, makes timing of harvest especially critical. Castor bean can exhaust the soil quickly, and regular fertilization is needed for continuous production of seed. Under irrigation, yields from castor bean can exceed 1,000 kg ha^{-1} (890 lbs. ac^{-1}) of seed regularly, and experimental tests in the U.S. and Brazil have given yields up to 5,000 kg ha^{-1} (4,450 lbs ac^{-1}). Although there is potential for very high oil yield from castor bean, the fact it is considered a weed by many agricultural producers certainly limits its viability as an option to produce significant amounts of biodiesel. As a weed, it has infested many pasturelands and crop fields across the State, leading to yield declines, equipment damage, and increased demand on human capital for control. Negative connotations associated with a plant can permanently shift a producer's mindset into one of refusal. Because castor bean is such a widespread weed in Hawaii, and because it can spread very easily, it is not recommended at this time to be pursued for use as a source of oilseed for biodiesel production.

3.13.8 *Simmondsia chinensis* – Jojoba

Jojoba seeds are unique in that they contain an actual wax, not oil. From this wax, oils can be expressed or extracted by solvents. The oil is highly-stable, and it has very similar qualities to sperm whale oil, which was used extensively around the world until the middle of the 20^{th} century. Jojoba oil is relatively easy to work with once extracted, as it needs little refining, does not become rancid, and can withstand repeated heating and cooling cycles in excess of 250°C (Duke, 1983). After expressing oils from the seeds, the remaining cake has protein content over 30%, making it suitable as an animal feed. The seeds may contain over 50% wax (oils), and they are approximately the size of peanuts.

The jojoba plant is a very long-lived species living up to 200 years. They are evergreen and grow to heights over 1 m. The plant is native to the desert areas of the southwestern North American continent, and it grows best in conditions ranging from warm temperate deserts through tropical deserts. Loose, well-drained, alkaline soils are best-suited for jojoba cultivation. Plants do not begin to fruit until about five years after establishment, and full potential isn't reached until 8-10 years after planting (Duke, 1983). Jojoba does have the potential to be spaced tightly into hedgerows for plantation-style cultivation. Yields from this plant could be expected to be between 1,125 and 2,250 kg oil per year from one hectare, or 1,000 to 2,000 lbs per acre per year (Duke, 1983), but other sources put the figure closer to 500 kg oil per hectare each year (440 lbs ac^{-1} yr^{-1}). Establishment costs can be expensive in barren desert settings, and in areas that are already set up for irrigation, costs are significantly lower. Although jojoba doesn't require much irrigation, in the dry areas which it thrives, access to water is of much more concern. Jojoba could be grown readily in Hawaii, particularly along leeward coasts. Tests to explore the feasibility of jojoba production could be carried out in dryland areas, especially leeward locations.

3.13.9 *Sapium sebiferum* - Chinese tallow tree

Chinese tallow tree is a tree native to much of central Chin and Japan. It has an oil content ranging from 24-32%, this total comprised of two different fats. The seed has an outer covering, referred to as tallow, which is solid, and the kernels produce oil known as stillingia oil (Duke, 1983). The tallow is used commercially for manufacturing candles, soap, cloth and fuel. The stillingia oil is used as a varnish and paint ingredient (because of its quick-drying properties), machine oils, and crude lamp oils. The oils have been used as a purgative and are not usually considered as vegetable oil for human consumption in Chinese tradition. Seed meal left after oil and tallow extraction possesses a high protein-content, and it makes a valuable feed and fertilizer. The meal can also be processed into high-quality, refined flour, superior to that of wheat.

Sapium sebiferum is a tree that is adapted to a variety of growing conditions, thriving along canal and stream banks, steep mountain slopes, sandy beaches, and alkaline, saline, or acid soils. Chinese tallow tree is adapted to many soil types, including peat soils and leaf molds. Annual precipitation over 1.3 m is best for productivity. Mean air temperatures must be between 15-30°C, and the tree may be propagated by seed, cutting, or grafting onto rootstock. The trees may produce fruit for up to 100 years, and can begin producing fruit in as little as three years after planting (Duke, 1983). Trees can be grown in plantation style settings with about 400 trees per hectare (160 trees per acre).

At 400 trees per hectare (160 trees per acre), yields of 14 MT ha^{-1} (12,400 lbs ac^{-1}) of seed could be expected under ideal conditions. Of those 14 MT, 5.4 MT (4,800 lbs) would be tallow and oil, with the remainder being protein material useful in animal fodder and shells and fibers for fuel (Duke, 1983). Reports have indicated that Chinese tallow tree could yield up to 25 barrels of oil per year per hectare as a sustained energy yield. Chinese tallow tree can also be utilized for biomass production. The trees coppice well and grow rapidly, allowing multiple grow-outs from the same planting. Taproot production, drought and salt tolerance, and rapid growth rate make Chinese tallow tree an ideal tree for biomass production along coastal regions. Once trees begin to decline in productivity of oils, they can be harvested for other energy purposes. After regeneration, they will again provide oils until harvesting is again necessary.

Table 3 Suitable pH range for selected crops

Crop	pH range	Crop	pH range
Soybean	6.0-6.5	*Jatropha curcas*	5.0-7.0
Sunflower	6.5-7.5	Pongam tree	5.8-7.5
Peanut	5.5-7.0	*Moringa oleifera*	4.5-8.0
African oil palm	5.5-7.0	Gorse	4.5-6.5
Kukui nut	5.0-8.0	Castorbean	4.5-8.3
Avocado	6.2-8.3	Jojoba	>7.5
Coconut	4.2-8.0	Chinese tallow tree	5.0-8.0

Old pineapple lands can be very acidic.

4. Infrastructure Demands

The development of a new market of biodiesel from oil crops will require significant investment in facilities to extract and process the oils. Decisions must be made on the scale of such operations. The choices made in regards to size of operations will dictate the type of equipment necessary for large-scale and small-scale plants. In the infant stages of this work, as research and development in oil crops are taking place, only small plants using mechanical extraction will be required for product testing and production technique analysis, i.e., harvest timing for ease and optimal oil contents. At early stages, only small investments in expelling equipment and methanol for the transesterification of the fatty oils into biodiesel will need to be made. The small operations on an experimental basis will also allow for development of uses for by-products of the process. Each crop chosen for experimentation will have slightly different qualities in the types and amounts of by-products, and the ability to find and create markets for such products will be addressed in the next section. After decisions have been made on what to grow, a step-by-step scaling-up to address the consumption needs of different sectors should be taken. This will allow for a steady expansion period in which problems can be addressed and some fuel needs can begin to be met. After some period of time at this stage, scaling-up operations to meet needs of entire islands could be considered.

4.1 Initial R&D

Research into crops for biodiesel production will need to be carried out over a period of five to ten years. Work needs to be done in a variety of locations throughout the State to identify areas in which growing conditions are well-suited for different crops. Each of these locations will need small testing facilities, or a centralized testing location could be established for uniform analysis of all products. The facilities must be equipped with extractors capable of handling one ton of seeds per day. By setting a standard for extraction, all crops can be accurately compared. Establishing this type of research lab on one island alone would reduce costs of equipment, but transport costs of raw product from island-to-island could be significant. A facility such as this could be incorporated into the Hawaii Natural Energy Institute at UH-Mānoa, or multiple facilities could be placed throughout the island that could work specifically on crops produced on those islands. If multiple smaller processing facilities were chosen for purposes of testing, the levels of feedstock could be greatly reduced, and the equipment could be scaled down to handle 200 pounds of seed per day for extraction.

There are several methods for extraction of oils from seed crops, including cold-pressing, screw-pressing, a combination of cold-pressing with heated extraction, and solvent extraction. Solvent extraction is the most efficient method of removing oils from seeds, but it has high costs for chemicals and safety concerns are much greater. For the simple task of researching the potentially extractable oils from such crops, mechanized cold-pressing followed with a heat treatment would be sufficient. On large-scale production, either quite large mechanized presses would be necessary, or the solvent method would be the most efficient manners to extract the oils. For the research, the combination approach would give yields somewhat lower than what would be expected through solvent extraction, but it would keep costs and risks at a minimum. After extraction from physical means, oils must be sieved to remove any shell fragments and seedcake that may have contaminated the oil.

Once oils are extracted, the fatty acids contained in those oils must be transesterified. This is achieved through a chemical reaction that takes place between the fatty acids in the oil and an alcohol, typically methanol. Ethanol, butanol, and other alcohols can be used for this, but methanol is the industry standard for biodiesel production. Industrial grade methanol is used. A concern here is the source of an alcohol. Is this just a substitution of one imported product for another, methanol for diesel? Fortunately, Hawaii has significant agricultural sources for alcohol production in the culls from its significant fruit production which can be utilized in making alcohols. This process would need to be developed concurrently; the point is a local alcohol source is feasible and within the agricultural communities.

There are two products created from transesterification: the 'dirty' biodiesel (known as FAME-fatty acid methyl ester) and glycerin. The glycerin can be easily separated from the FAME through physical means, but the FAME must have the methanol removed through distillation. After distillation, the biodiesel must be thoroughly washed and dried before it can be burned. Any moisture or contaminant particulates will decrease the burning efficiency of the fuel, thus skewing results in any analysis. Biodiesel must meet certain ASTM requirements to be burned in automotive engines, so Quality Control (QC) will be a fundamental part of the process.

By cultivating a variety of crops in various locations in the Islands, there will be better preparation to move forward into commercial production of crops. The detailed physical and chemical analysis that will follow for each of the oils extracted from individual crops will be the most important factor for determining which crops to pursue. Agronomic information must be combined with such analysis to determine the proper combinations for successful biodiesel production in Hawaii. Once this data has been duplicated over a period of three or more harvest cycles will there be enough information to expand to the next step of commercial biodiesel production in Hawaii.

4.2 Small-scale facilities for agricultural producers

As in any commercial development it would be very risky to go from R&D to large-scale production of biodiesel from oil crops. To ensure success, there will need to be small-scale operations instituted to address needs of one sector of the diesel-consuming populace. The farm environment would be an optimum location to implement small test facilities for production and processing of pure biodiesel (B100). Agricultural producers have very high rates of diesel consumption, access to land for potential use, experience in developing new cropping systems, and access to a community that can help in expanding the visibility of markets. Centrally located small-scale operations in agricultural communities could function as cooperatives among farmers where they are the suppliers and customers of the biodiesel. There are modular-type processing facilities capable of producing 78,000 gallons (295,000 liters) or more of biodiesel per year that could be used to scale-up or scale-down to meet local demand. The establishment of such cooperatives could serve the needs of rural communities for some transportation fuels outside of agricultural producers. Such cooperatives of small-scale production could focus on supplying the needs only for a small area of an island, and develop by-product markets for their local region. Incentives and government policy for biodiesel development would stimulate the initial stages of development as well as utilization of the available federal grant programs for cooperatives.

Using data presented in Table 2, an area of 260 acres (640 hectares) of Jatropha trees could conceivably produce enough seed to supply a conversion facility with oil to produce 78,000 gallons of fuel per year. Following and supporting the development of any small cooperative in meeting the demand of an agricultural community would be part of the implementation process. Encouraging expanding plantings of desired oil crops, increasingly larger scale harvesting operations can be studied for efficiency and plausibility. Future improvements by engineers, researchers and producers should be possible as planting sizes increase and assuming the support community efforts are directed to this area.

A significant advantage to creating such small cooperatives to meet localized demand is the lack of necessary transportation of fuel to larger markets immediately after oil crop implementation has occurred. True estimates of potential production could be established without interference from outside industries. When other consumers begin to convert over to biodiesel blends, the supplies will have to be transported from rural areas of production to facilities that can develop the appropriate mixes based on available supplies. The production of biodiesel in rural areas also could account for a decreased of imported fuels and their transportation needed for electricity production in rural areas. Instead of shipping petroleum-based diesel fuel, or No. 2 heating oil, to small power plants, these locally based cooperatives could contribute to the power supply, creating more self-sufficient communities. Even if areas identified for oil crop production are easily accessible by a developed roads' system there are benefits to a reduction in transport of liquid fuels and unprocessed seeds.

Personnel would include a director for each small cooperative, to be decided up by the members, a staff to manage the receipt of crops, extract oils, process the fuels and market by-products. Having multi-tasked crews that could perform all tasks would be of benefit to the cooperative and provide skilled employment opportunities in the community. The investments would be in land, equipment (farming and oil extraction and processing), training, QC, and in safety certifications and meeting EPA regulations.

4.3 Large-scale facilities for island-wide consumption

One scenario is for each island to develop at least one large-scale plant for producing enough biodiesel to help meet some predetermined quota - self-imposed or otherwise - for replacing petroleum diesel. The determination of what blends will be possible won't be known until further analysis and research have been completed. If blends are pursued, large facilities that can produce millions of gallons of biodiesel annually will need to be designed, constructed, and managed. One important issue to consider will be the blending, storage, and distribution of the blended product. The two oil refineries, operated by Chevron and Tesoro, currently supply the petroleum diesel, and they have the facilities, engineers, and training to work with petroleum based fuels.

Another serious issue that must be addressed before widespread adoption of blended biodiesel or pure biodiesel can take place is the issue of vehicle modification. Most diesel consumption in Hawaii is by non-highway users (DBEDT, 2005), and non-highway diesel does not have to be as 'pure' as diesel used for highway vehicles. Highway use diesel has lower sulfur content than non-highway diesel, and biodiesel does have low sulfur content in most cases. Non-highway use, or off-road use, is categorized as any fuel that can be used as heating oil, in stationary engines, in non-highway engines, such as those in agricultural vehicles, and in separate engines mounted on highway vehicles according to the IRS's tax code. Biodiesel is a much safer alternative to petroleum-based fuels, as it is hardly flammable, non-poisonous to humans or animals, and burns cleaner during combustion. However, it can have adverse affects on engines. Many engines must be outfitted with special gaskets that are resistant to breaking down after usage of biodiesel. Conversion of engines is a consideration in using partial or pure biodiesel. As is the case with the conversion to ethanol, new vehicles will need to be compatible with higher percentages of biofuels.

The use of biodiesel for non-highway purposes may be a less-complicated transition than converting vehicle engines. Biodiesel can be used in blended or pure forms as a replacement for petroleum-based No. 2 heating oil. Biodiesel does not produce quite as much energy per unit burned as No. 2 heating oil, but it does reduce emissions of sulfurous oxides. Interest has been shown by multiple electricity providers across the State to have another fuel to burn in boilers. Biodiesel, when produced in bulk, may be an economical replacement to imported petroleum. Only slight modifications would be necessary to boilers currently used in Hawaii's electricity-generating facilities.

The construction of a large facility for biodiesel would eventually take place on each of the main islands. Again, it is recommended that modular systems are sought out for this purpose. If the different factories are determined to be operating below potential capacity, expansion is easily accomplished, and if they are found to be unprofitable, the closure or selling off of one or more modules can be transacted without losing time or capability to continue production. If each module were capable of converting 250,000 gallons (over 946,000 liters) of biodiesel per year, then an operation with twenty modules could supply 5 million gallons yearly. In off-periods with poor crop yields, modules could be shut down temporarily until they were needed. Several companies throughout Europe have developed modular systems for biodiesel conversion. These modules range in capabilities from 300,000 liters per year up to over a million liters per year (78,000 gallons to over 260,000 gallons per year, respectively).

Personnel and equipment for a large facility which includes large farming operations to produce a biofuel would be substantial. Depending on the crop selected equipment needs can vary greatly. Multiple pieces of equipment for each task would be necessary and most farm equipment ranges from $70,000 to $250,000 new. Adaptable equipment in use in the islands already will be one way to keep such farm equipment costs down. Personnel is an operations major expense as well as another scarce resource in agriculture, so the automation of as much of the field work as possible will be important to any large operation. Keeping farms managed to allow for almost continuous harvesting will also require individuals with expertise in crop cycles. Managing tree crop cycles requires different expertise than for field crops.

A large facility will require that trucking take place to transport fuels to blending and/or distribution points, the location of which will have to be determined. The economics of whether to outsource or internalize this function is a factor to consider. A large facility will also need to evaluate the market for co-products. The development, marketing, and distribution of such co-products will require dedicated capital or committed research support. Primary providers of biodiesel will need to consider being vertically integrated in the marketplace to capture value added benefits of co-products. Encouraging markets for conversion systems for vehicles to run on B100, manufacturing of specialty products from biodiesel co-products, opening up fuel stations with other business ventures, and developing a positive public image of their products will all greatly aide any company engaging in biodiesel production.

The biodiesel supplier currently in Hawaii is Pacific Biodiesel. It has refining facilities in place for converting waste vegetable oil (WVO) to B100, but does not have the experience in crop production for extraction of oils. It is close to maximizing its potential production from WVO, which will be up to 2 million gallons annually statewide (King, 2006). The acquisition of enough land to produce over a million gallons of biodiesel will prove to be difficult, since leased farmland and water are expensive. The best scenario to supply all diesel needs for an island would be to find a crop that can out-produce any other, perhaps oil palm, microalgae, or some other very high oil content tree. A field crop that requires significant irrigation and fertilization rates while providing a reasonable return for a biodiesel producer is unlikely without incentives and/or high value co-products, yet to be identified. The agricultural production economics may have more influence over realistic biodiesel yields than the processing facilities. Without better local agronomic data for the potential oil crops, determining reasonable economic projections is not practical. Field research into this area is part of the infrastructure development needed at this early stage of crop biodiesel production in Hawaii, while co-product development will be important to its long term sustainability.

5. By- and Co-product Market Development

The process of manufacturing biodiesel from oil crops provides four or five pretty standard by-products. Co-product in contrast to by-product development will be important to the long term economic viability of fuel crops. The distinction is necessary so that the proper attention and resources are directed to this area. Depending on which crop is selected for production, the by-products can vary slightly from one crop to another. The primary by-products that all conversion processes can produce will be discussed in short detail. Properties can change based on quality of feedstock, amount of oil successfully extracted, and any unusual chemical substances, potential co-products, that some crops may have present in their residues. It is important to consider the relative lack of knowledge about such products in Hawaii, because as production of biodiesel gets underway, there will be an opportunity for materials engineers and scientists to develop high value co-products to improve the viability of an agricultural biodiesel sector.

5.1 Glycerin

The main by-product from biodiesel manufacture is glycerin, which is also referred to as glycerol. It can be separated via physical means from the transesterified FAME by simply pouring it off the surface of the biodiesel portion. Glycerin is a primary ingredient in soap-making and other cosmetics. The quality of the glycerin will vary slightly from crop to crop, but similar proportions can be expected from conversion of each oilseed. After transesterification, approximately 85% to 90% is the final biodiesel product, and the remaining 10% to 15% is glycerin.

Glycerin is a sugar alcohol that is colorless, odorless, and has a semi-sweet taste. Aside from soaps and other cosmetics, glycerin is sometimes used in foods as a sweetener, in chemistry applications, and, at one time, as an ingredient in explosives. The glycerin that is produced after the transesterification process is in an impure form (90-98% pure) that needs to undergo further distillation to be pure enough (>99.2%) for other industrial utilization. This process can be done in the biodiesel production facility, or it can be sent to other specialized facilities to be processed. Only the refined, pure vegetable glycerin should be used in food products.

In pharmaceuticals, glycerin is used as a means to increase smoothness, provide lubrication, and as an ingredient in cough syrups and expectorants. Glycerin is used as a sugar substitute in some foods, a softening agent in some candies, filler in low-fat foods, and as a solvent for flavorings such as vanilla. Glycerin is hydrophobic, so it must not be ingested without dilution, as it can cause blistering in the mouth and digestive tract. Glycerin is a primary raw material for production of flexible foams and other synthetic plastics.

A recently applied-for patent is attempting to address the over-production of glycerin with the advent of increasing biodiesel production around the world. With the overwhelming of the glycerin market, prices will fall, making one of the by-products from biodiesel production nearly worthless. In Europe in 2005, government intervention requiring increased biodiesel consumption has pushed the prices for glycerin very low, thus punishing biodiesel producers for being successful. An invention has been made that converts glycerin to propylene glycol, which can be used commercially as antifreeze for engines and as a de-icer for aircraft. A conversion rate of over 90% had been successfully demonstrated by three scientists in 2005 (ACS, 2006).

Excess glycerin in Hawaii would be used in the manufacture of Hawaii's specialty cosmetics, as an ingredient in foods, and, for propylene glycol, if conversion proves successful and a market in Hawaii exists for it. The specialty soaps market is the most likely area for profitability in Hawaii, as any products could be marketed locally to the hotel industry, to mainland and international customers as produced in Hawaii as a natural by-product from biodiesel conversion. Soaps currently produced in Hawaii use such techniques to infiltrate markets outside the Islands and those soaps could also benefit from locally-produced glycerin with which to make their soaps. Products developed locally have international appeal, and that appeal has been capitalized on for decades; it is likely this trend can continue in coming years. The use of glycerin in foods in Hawaii could help lower fat content in locally produced and processed foods.

5.2 Uses for seedcake remnants

The seedcake that remains after the oils have been extracted from seeds can have many uses. Regardless of whether the seeds have their oils extracted by mechanical or chemical methods, the seedcake that remains (often referred to as 'presscake') can be rinsed and dried to produce a solid substance with potential for applications in agriculture and other energy production. Some possible uses for seedcake are as organic fertilizer, animal feed, and charcoal. The remaining seedcake could also be fully dried out and combusted for energy to run processing facilities, much the same way bagasse is used by sugar plantations. The organic residues could also be used for gasification, a technology on the horizon that can be used to produce ethanol.

The use of seedcake as organic fertilizer or animal fodder may prove to be a very worthwhile market for biodiesel by-products. The potential for fertilizer develops when extracting the oils through the transesterification process, during which a catalyst must be used. The most commonly used catalysts are potassium hydroxide (KOH) and sodium hydroxide (NaOH). The KOH is more commonly used as a catalyst, as it is more soluble in methanol (the preferred reagent for transesterification) than is NaOH. After the process has converted the vegetable oils into biodiesel, the remaining cake must be dried out before it can be mixed into animal feed or used as a biomass fuel or fertilizer.

Depending on the crop used for biodiesel production, the qualities of the seedcake will be variable. Different seedcakes will have different ratios of proteins, lipids, and carbohydrates, producing varying products for use as animal feed. When crops have been isolated for field-scale experimental trials, the access to leftover seedcake will allow for detailed analysis of the nutritive characteristics each cake has. Some potential sources for biodiesel production have seedcakes with toxic substances, making them unfit for use as animal feed. Examples of these plants are jatropha and castor bean, containing curcin and ricin, respectively. In instances where these crops would be used for oilseed production on a commercial scale, there are methods to detoxify seedcake for use as feed, but the process may prove to be more costly than is realistic for such operators to undertake.

Flakes of dried algae

The premise of using the leftover biomass after oil extraction has been in practice for decades. It has long been accepted that these 'meals' have high protein content, and many materials, such as the dried algal biomass pictured above, have proven to be as high quality of feed as other products currently available to livestock producers such as fish meal and blood meal. Other high-value products may also potentially be extracted from these leftover meals, including pharmaceuticals, cosmetics, and supplements.

Regardless of potential toxic substances that may be found in a plant's residual seedcake, that cake will certainly be usable as an organic soil fertilizer. As with animal feeds, each seedcake will have slightly different elemental compositions that must be determined during R&D trials conducted in early stages of implementation. Many seedcake substances have properties very similar to animal manures. Jatropha seedcake has an elemental makeup very similar to that of chicken manure, with 6% N, 3% P, and 1% K. Soybean meal has a fertilizer value of 7% N, 1% P, and 2% K. These values will be similar for most seedcakes that are remaining after oil extraction has taken place. Each of these cakes will act as mulches and slow-release fertilizers, and they also provide alternatives for organic producers or other farmers who may wish to utilize natural methods of fertilization over chemical fertilizers.

A final use of seedcakes that remain after oil extraction is for them to be recycled as another source of fuel. There will always remain a small percentage of the original oil content of the seeds after extraction. The combination of this small amount of oil and the biomass residues left over provide a natural source of heat when combusted. In both large and small facilities, this excess seedcake could be utilized as a heat source for the extraction process, and it could also be turned into fuel pellets for burning in stoves, boilers, furnaces, or other heating and cooking purposes. If extremely large volumes of this cake were accumulated, the cake could be used for electricity generation at a power plant by co-firing with coal or other biofuels.

5.3 Residual biomass

At time of harvest, many row crops such as sunflower and soybean will leave significant amounts of residual biomass in the field after seed harvesting operations have ceased. This biomass may serve two purposes. The residues can be incorporated into the soil to provide organic matter that will improve soil conditions for the next crop. The residues could also be collected from the field, dried down, and used as a source of fuel for heat or electrical generation. This added operation would increase costs, so it is most likely that such residues would be left in-field.

Perennial oilseed crops will not supply as consistent a supply of residues for alternate uses, but when trees that bear oil for biodiesel production are grown, the amount of biomass available when the trees go out of production can be significant. Not only can these crops supply biomass for generating heat and electricity, but they may also be utilized for production of another liquid biofuel of importance - ethanol. If the technologies utilizing biomass for ethanol production prove effective, then there could be periodic harvests of non-productive oilseed trees and crops to supplement other ethanol production in the islands. Even though the amount of ethanol potentially available would be small, it would still serve to help meet Hawaii's demand.

Other biomass that will be available from biodiesel production will vary depending on the species that are isolated for planting. Coconut supplies generous amounts of copra and fiber that can be dried out and used as fuel. Many oil-bearing nuts and seeds have significant amounts of seed hulls and kernels that can also be dried down for use as fuels. Fast-growing oilseed-bearing trees may be pruned each year, supplying yearly harvests of biomass for alternative energy. A study on palm oil production in Malaysia identified large volumes of process residues that can be used as fuels, including fiber (from the seedcake), shells, and empty fruit bunches. It was determined that these materials could be densified into briquettes and used as a heating source for the processes within the palm oil processing mills (Husain, et al. 2002). These briquettes showed high structural integrity under hydraulic pressing, moderate heat-generating capabilities when combusted, and the ability to withstand wetting. Simple product development such as this may supplement any biofuels operations that are developed in the future.

5.4 Food products

Many herbaceous and woody oilseed bearing plants have historically had their oils utilized for human and animal consumption. To develop a successful biodiesel operation, high-value by-products are essential. Food products for human consumption can make for excellent supporting revenue for a bioenergy producing entity. Because the oils extracted would be directed into energy streams, the opportunity for edible oils marketing is non-existent. Some oil bearing plants have other properties that may lend themselves to specialized food product development.

By harnessing the marketing power attached to the State of Hawaii in any natural products, attempts should be made to isolate special food products that could be marketed as environmentally-friendly (due to their origin as a by-product from biofuel production) and native Hawaiian products. One example of such a product would be dried copra from the mesocarp of coconuts. If coconuts were produced for biodiesel manufacture, the remaining copra after oil extraction could be dried out and marketed as a Hawaiian product for human consumption. Identification of products that can be easily rendered from the by-products of biodiesel could create a new wave of marketable goods for Hawaii's economy. One caveat within this concept is that if the oil has been extracted and the pulp of whatever seed used is dried out, the spoilage of such products would be minimal, allowing for exporting all around the world, as opposed to dealing with many of the issues inherent in fresh produce exporting.

Another food product which may prove ideal is not directly produced by the oil producing plants themselves. Establishment of apiaries within certain crops could open up a whole new market for Hawaiian agriculture - the honey market. Significant production of honey currently takes place in Hawaii, but the establishment of large plantings of flowering plants would provide the necessary environment for large-scale honey production. Currently, most commercial apiaries are located on Big Island. The isolation of plants that can produce high quality honey would almost instantly create a secondary market to the production of biodiesel. The flowering tree crop *Jatropha curcas* is said to supply bees with blossoms that have pollen capable of producing a very high-quality honey (Openshaw, 2000). Other tree crops such as Chinese tallow trees, Ben-oil trees and avocados also attract numerous bees. Flowering plants that do not self-pollinate would also benefit from the presence of bees.

5.5 Unidentified chemical compounds

There is a wholly unknown aspect of the development of large-scale production of oil-bearing crops. Many of the crops grown in temperate climates for vegetable oils have been studied extensively, and many compounds have been identified from those plants. Working with tropical species in a developed economy such as Hawaii's would allow for an expansion of research into unknown or little-studied plants and their naturally-occurring compounds. The infrastructure is in place to develop new chemicals from identified compounds from extracts of any tropical plants that may be part of a biodiesel production scheme.

The isolation of unique compounds and extracts from tropical plants has shown tremendous potential to find treatments and cures for a variety of conditions and illnesses. History has shown that tropical flora contain many beneficial naturally-occurring compounds in their oils, latex, bark, leaves, and fruits. Many of the crops that could be potentially used for biodiesel production have previously been studied for economically beneficial extracts that may be present. It is expected that with diligent experimentation, more compounds from a wide variety of plants could be discovered that have valuable applications.

Tropical plants have had insecticidal, medicinal, and cosmetic substances extracted from them in the past. For example, parts of neem, pongam, and jatropha trees have been used for centuries by people in rural communities throughout the tropics to control certain agricultural pests. Substances found in castor bean and jatropha have been used as purgatives for remedying intestinal disorders. Jojoba has been used as a conditioner for skin, and oleoresin from *Copaifera sp*. has been used as antibacterial rubs. Exotic tropical plants are typically promoted as having the potential for great medicinal research, but even plants that may be cultivated around the world in large plantings may have valuable isolates that could have economic value to those who cultivate them. Such compounds would need to be identified through research plantings to determine if alternate markets may exist for a particular oilseed crop.

6. Three Scenarios for Biodiesel Production in Hawaii

One of the primary intentions of this report is to present three scenarios for biodiesel production in Hawaii. Through the process of conducting background research into land capabilities, possible crops, available infrastructure (or needed infrastructure), and potential for by-/co-product market development, the three scenarios have been broken down into the following detail. Scenarios could be developed on an island-by-island basis, region-by-region basis, or some other means, but this report has chosen to present scenarios based on level of productivity and investment in capital. These three options for production of biodiesel from oilseed bearing crops are given in the following sections.

6.1 Production by individual farmers

For centuries farmers have been utilizing plants and waste materials to supply their own personal heating fuels and, to a lesser extent, their own liquid fuels. As mentioned for various crops and trees identified in Chapter 3, oils have been extracted by rural farmers and others in farming communities to meet lighting and heating oil needs. With the technological advancements that have taken place since the mechanization of agriculture over the last 80 years, the ability of even the smallest farmer to produce biofuels on-farm has become more realistic. Farmers can now utilize biomass and oil crops grown on their own land to run their own equipment.

The small farmers in Hawaii that own or lease enough land to meet their own biodiesel needs could invest in small hand-operated or larger hydraulic-driven presses for extracting oils from the crops they choose to implement on their lands. Hand-operated presses range in price from $350-$2,000 depending on the size, design, and manufacturer. Some of these hand-operated presses can process up to 100 kg of seeds in one hour, but the labor needed to operate them is significant, as they typically require at least two people to operate. Hydraulic presses can range from $1,500-$5,000, with processing capabilities up to 200 kg of seeds per hour. The labor requirements for hydraulic presses are less than for the hand-operated ram- and screw-type presses.

Assuming each piece of farm equipment using diesel fuel (tractors, haulers, dozers, etc.) uses approximately 3,000 gallons (11,350 liters) of fuel per year, a small farmer with only one piece of equipment would need about 4 acres (1.6 ha) of oil palm trees, 10 acres (4 ha) of jatropha trees, or about 12 acres (4.9 ha) of land for a rotation of soybean-sunflower-peanut to meet his own fuel needs on a yearly basis (based on info from Tables 2 & 3 in Chapter 3). Most small farmers will not have sufficient land to grow such crops, especially considering the particular climates and soil qualities necessary for production of crops such as soybeans, peanuts, or oil palm. The fuel value assigned to an average farmer's piece of equipment is an arbitrary one, so possible fuel uses may be as little as 1/3 of the 3,000 gallons referenced. Each individual farmer would need to have external support to develop a plan to implement a self-sufficient biodiesel production operation.

A small farmer may not be able to implement such a program due to land, time, labor, and equipment limitations. Larger operations that operate on greater than 100 acres would have more resources available to devote to biodiesel production for on-farm sustainability. Although large operators will have greater fuel requirements, their access to more marginal lands that could be dedicated to oil crops and the labor necessary to harvest and process those crops will work in their favor. Large landholders will also need a strong support and research system in place to maximize efficiency in production.

The individualistic approach to biodiesel production on a farm-by-farm basis could lead to some excess biodiesel available to those outside of the producers themselves. This method of producing biodiesel could meet the needs of some of the rural communities across Hawaii, and a support system would have to be in place to assist with the cropping and processing operations. Each producer would need site-specific recommendations for crops that could be used for biodiesel purposes. Training would also be necessary for each individual that would wish to pursue individual production for use on-farm. The processing is not technically difficult, but it does involve handling of flammable and caustic materials, and storage facilities must be maintained to meet safety and health standards.

6.2 Organized co-operative production in rural communities

A community-oriented approach to biodiesel production could serve entire rural regions of Hawaii, producing sufficient amounts of biodiesel, a cleaner-burning sustainable fuel for those communities. The establishment of biodiesel co-operatives (CO-OPs) in rural areas might involve numerous landowners and farmers in the development of a sustainable biodiesel production and distribution scheme. Possible schemes follow.

The concept of energy CO-OPs to serve rural communities has its roots in the co-operatives that have been developed over decades in rural and agricultural communities to more easily facilitate the distribution of essential specialized goods to those in the community. By developing energy CO-OPs, each landowner or lessee could participate to some degree in the crop production, and have access to all the biodiesel needed for their own operation. Farmers and landowners would enter into contracts with the CO-OP to set aside parcels of land for biodiesel crop production.

The CO-OP would be in charge of all harvesting and processing operations, taking care of much of the direct costs of labor that would exist for farmers producing their own fuels. The concept behind the CO-OP would reward farmers/producers for successful production of the designated oil crops. Each grower's yield could be credited towards their annual fuel use, allowing for a built-in system of motivation for effective production of the crops. By the landowners' donation of their land, water, fertilization, and any other inputs necessary, discounted fuel could be provided based on their level of productivity.

Farmers and landowners with minimal amounts of available land to dedicate to oil crops could place small areas into production in order to take advantage of the discounted fuel supplied to the region of the Island. Those entities that dedicate hundreds, or even thousands, of acres to biodiesel crops would have access to large amounts of the biodiesel, and if more fuel is supplied by a grower than they individually use within a given time period, those growers will be paid out a pre-determined value for their production. Income for the CO-OP would come from sales to non-members of the CO-OP. Interests of industry and energy suppliers in the cleaner-burning biodiesel for environmental and tax-break purposes would help drive the markets for biodiesel outside of the agricultural sector.

Like with individualized production of biodiesel crops, a multi-layered support system would be necessary in the agronomics and processing specifics to maintain production on behalf of each of the CO-OP members. Ideally, the focusing of CO-OPs in different regions of each island would allow for more uniformity in the crops grown. Uniform crop production would make the harvesting operations of the CO-OP simpler and less time-consuming in regards to equipment needs and processing facilities. Use of agronomic information and recommendations for each CO-OP would help to isolate one or two crops to be grown within each region. The distribution of information between CO-OPs would also be beneficial to the entire State's production scheme.

A benefit of developing centrally-located CO-OPs within Hawaii's agricultural communities is the expected acceptance of farmers and landholders for the new land uses that would need to be undertaken if biodiesel production is to be implemented on a large-scale. Widespread acceptance of new crops in Hawaii by producers and landholders will help facilitate continued expansion of biodiesel markets. Primary consumption of diesel fuel in Hawaii is by industrial entities, but the provision of biodiesel must be undertaken by the agricultural community. Because of this relationship, focusing biodiesel consumption in the rural communities initially will help foster support for the fuel.

Regional CO-OPs could function under one umbrella across the State or within an Island, and the collective could function as a source of R&D for further innovation. By concentrating production into these CO-OPs, alternative uses of by-products could be developed, and the isolation of useful plant compounds could be focused within special facilities overseen by the CO-OP. In this way, the CO-OP would also serve its constituents by providing supplemental income through potentially patentable products which would come from the plants grown by the members.

Operations within these CO-OPs would be based from the centrally-located collection and processing facility. This would also serve as the distribution point for all members and non-members to 'fuel-up' equipment and vehicles. Each contributor would be granted some sort of dividend for fuel allotment annually, and contracts could be developed with non-contributing members and non-members for their fuel requirements. Based on the volume produced transport off site to distribution centers could be developed.

The development of rural co-operatives is a project that can garner support through the pursuit of grants from the USDA Rural Development agency. Support from the State to promote such facilities during the implementation stage and for a definitive number of years would encourage the establishment of such entities. Cooperation between CO-OPs established and the research community would help in expanding operations into co-product development and utilization.

6.3 Large-scale plantations of oil crops

A third potential option for biodiesel implementation is to establish large-scale plantations of oil crops. The development of large plantations of energy crops is a scenario that would entirely privatize the biodiesel sector in Hawaii, isolating production to a few large entities. As with ethanol, to implement this form of energy farm tax breaks and other enticements to investors may be needed. A scenario where large plantations produce biodiesel would likely lead to one or two operations per island.

There are landowners in Hawaii with access to significantly large parcels of land that could be brought into the biodiesel production market. The regions isolated in Section 2 were selected for the reason that large-scale plantations may be an efficient way to produce biodiesel in the long-term. By identifying large landowners including state lands who have lands that could be utilized, it is possible that those landowners will see the benefits of setting aside some significant acreage for biodiesel crop production.

To develop a scheme of biodiesel production in plantation settings, it is most likely that the crops chosen for each plantation would be uniform within each farm. Because agronomic, harvesting, processing, and fuel qualities and properties will be different for each type of crop used, most large operations would prefer to be in a mono-cropping system with as many of the operations automated and mechanized as possible. Large operations of this scale rely on highly-efficient use of labor and equipment to maintain profitability.

If each island had one or two primary providers of biodiesel, the producer would likely develop at least one of the primary by-product markets as a single-stream, meaning that the large operations would choose the most plentiful by-product that could be easily marketed and sold as a means of sustainable production. Co-product development would be evaluated as needed. A large plantation would be in a position to use wastes and residues more effectively than any other operation, as sugar plantations have found the most efficient way to utilize bagasse, the primary by-product for the processing of sugarcane, for energy. In the same way, some of the residues and leftover biomass from biodiesel manufacturing may also be used to provide fuel for co-firing operations to supply electricity to the grid of each island.

Programs could also be developed by the State to facilitate relationships by large landowners who wish to maintain their holdings and investors that may wish to begin large-scale production on those lands. Because many of the large landowners across the State (Castle & Cooke, Kamehameha Schools, Campbell Estate, the Hawaiian Home Lands, State of Hawaii, C. Brewer & Co., and several large ranches) are not currently involved in entrepreneurial endeavors relating to biofuel production, the State may want to encourage these landholding entities to set aside large parcels (over 5,000 acres) for interested firms. An expected leader in the pursuit of such lands might be Hawaii's lone biodiesel producer, Pacific Biodiesel. If Pacific Biodiesel were to develop a successful partnership with a large landholder, it would provide the model for other firms to partner with landholders for potential investment of capital for biodiesel crop implementation. The development of large-scale plantations of biodiesel crops could create an effect on Hawaii's diesel market, decreasing demand for imported petroleum diesel almost immediately upon the first harvests. The supplies would reach all sectors of Hawaii's economy, from agricultural to industrial to commercial. It is expected that demand for biodiesel will be high upon its increased availability, and the development of large facilities would help meet such demand. Because many companies are looking for new ways to become more energy efficient and use cleaner burning fuels for tax incentives, the biodiesel produced in the Islands should be easily marketable. A large producer/processor/distributor could capitalize on the rush of other industrial sectors to meet or exceed environmental standards.

7. Production Schemes

The following sections outline potential for production of biodiesel crops on each of the seven main Hawaiian Islands. Yields given for each location on each island are extrapolated based on data included within this report. Many assumptions must be made to reach these values.

7.1 Ni'ihau

Ni'ihau has the potential to supply all of its diesel fuel needs. Lack of available moisture is the primary limiting factor on Ni'ihau. Crops that are highly-efficient users of water must be utilized. Crops that have potential for use are jatropha, coconut, neem, pongam, *M. oleifera*, gorse, castorbean, or jojoba. Each of these crops can survive with approximately 20" of annual precipitation or less. Some would require very minimal and timely supplemental irrigation. Depending on the availability of supplemental irrigation, these crops may warrant investigation.

Working under the assumption that less than 5,000 gallons (18,900 liters) of diesel fuel are consumed by local residents and naval operations yearly, it would be possible to supply all diesel needs with less than 25 acres (10 ha) of a selected oil crop. Supplemental fertilization would be necessary on Ni'ihau to maintain any productivity. Processing equipment and storage containers would either need to be in place on the island, or such facilities would need to be located on Kauai where supplies could be easily shipped over to the local population. Because little is known about the landscape of Ni'ihau, it can only be assumed that the location of such production would need to be nearly adjacent to the primary community at Puuwai.

J. curcas could be planted on Ni'ihau to supply biodiesel for the island. Using the island's average annual precipitation, jatropha could flower and fruit once per year with no irrigation necessary after establishment. During the first 18 months of growth, jatropha would require some supplemental irrigation. This may strain freshwater resources on the island initially. After establishment, fruiting would occur directly after the wet, cool season subsided. If planted to approximately 2,500 trees per hectare (~1,000 trees per acre) - the recommended rate - jatropha could supply 7,500 gallons (28,400 liters) of oil for biodiesel processing on 25 acres (10 ha). This total is expected to surpass annual consumption, allowing for slightly lower yields than are customary due to fluctuations in precipitation and nutrient levels.

After each annual fruiting cycle, local residents could harvest the nuts by hand as they yellow on the trees, or after they have completely ripened and fallen from the branches. During harvest season, daily collection would be necessary. Nuts collected each day could be processed and have oils extracted immediately after collection using a hand-driven or hydraulic press. Local residents would require training in each facet of crop production and maintenance, as well as extraction, processing, and storage. By-products could be used as organic fertilizer in the jatropha planting or in Ni'ihauans' gardens.

The recommendation for Ni'ihau should be considered speculative. Much depends on available land and the willingness of the local population to participate in such a project.

Other crops that may have potential uses are castorbean, jojoba, or pongam. Survey of potential land should be conducted prior to any crop establishment on Ni'ihau.

7.2 Kauai

Three locations were outlined on Section 2.4 for Kauai. Using information from those three locations and the crops outlined in Section 3, estimates can be made for total potential biodiesel production for the island.

The area of Kauai that makes up the Mana Plains on the leeward coast is currently used for significant areas of seed corn production. The climatic conditions at this location suggest that a relatively drought-tolerant crop would be best suited for biodiesel production. The use of jatropha trees planted in rows similar to coffee could supply approximately 3.3 million gallons (12.5 million liters) of oil with two cropping cycles per year, thanks to supplemental irrigation. This is assuming the scale of operations at 5,500 acres (2,220 ha). The natural climatic conditions would allow for one crop grown from precipitation and one crop grown with irrigation as its main source of water.

The leeward coast of Kauai adjacent to the Mana Plains receives abundant sunshine year-round. This area near PMRF, a naval facility located along the coast, could also serve as a test location for algae ponds. As detailed in Section 3, microalgae may be a long-term solution for oil production in Hawaii. Isolation of the proper climatic regions to locate raceway-style ponds is an important first step. Whether Kauai is a suitable location for this means of oil production in the future, remains to be determined.

The area near Koloa that was detailed in Section 2.4 would constitute an area of only about 1,400 acres (560 ha). With its rainfall and temperature information, it is believed that this area would be well-suited for African oil palm. Estimates taken from Section 3 information on oil palm potential suggest that about 1 million gallons (3.8 million liters) of oils could be produced from this parcel. Some small amount of supplemental irrigation may be necessary where rainfall does not exceed 60" per year.

The final region isolated in Section 2.4 was the area north of Lihue in the Lihue Basin. This area of approximately 1,800 acres (4,440 ha) would also support oil palm. Using the same information as for the Koloa region, over 1.35 million gallons (5.1 million liters) may be producible in this region. Climatic conditions in the Lihue Basin should be very favorable for oil palm production, and no irrigation should be necessary.

Other areas of Kauai's windward, northern, and southern coastal-lowlands have potential for oil palm utilization. Although not outlined in this report, these areas are extensive, and they may be able to supply anywhere from 2-8 million gallons (7.6-30.3 million liters) more oil for biodiesel processing. Compiling information from the three specified locations on Kauai, total biodiesel generation for the island would be greater than 5.6 million gallons (21.2 million liters) per year. This is almost 30% of Kauai's total diesel consumption for the year 2004 (>19 million gallons). With an additional 5 million gallons (18.9 million liters) of production from other locations, Kauai could replace nearly half its petroleum-based diesel with biodiesel.

With Kauai's past and recent history as a rural island with significant agricultural production, the development of lands for oil crops is feasible. Necessary inputs such as fertilizer and irrigation are readily available on the island. Abundant rainfall and multiple reservoirs supply sufficient freshwater for crop production. Many of the lands on Kauai once used for sugarcane production have been fallow for some time. The areas specified in this report may have other agricultural production activities currently in operation precluding their use for biodiesel crop implementation. These figures serve as an estimation of potential for fuel production should those lands be converted from fallow conditions or other production into biodiesel crops.

The necessary infrastructure to support operations of oil palm and jatropha is already in place. Some transportation design and maintenance issues may need to be addressed to account for increased agricultural traffic along certain routes. Equipment necessary for tree crop operations is either in place or could be imported readily. Utilization of coffee harvesters for jatropha harvesting would permit some cost-sharing if deemed feasible. Mechanization of oil palm operations would be important for its profitability. The seed meal and pulp by-products from these crops could serve two primary purposes. Jatropha, due to its toxicity, would provide a high-quality organic fertilizer, and oil palm remnants make a relatively high-value livestock feed.

7.3 Oahu

Three areas of Oahu were considered as possible locations for the implementation of biodiesel crops in Section 2.1. The first region is the North Shore/Waialua/Kunia area of old sugarcane and pineapple lands. The second region is on the leeward coast, upslope of Waianae and Nanakuli. The third area is on Kamehameha Schools land along the North Shore from Haleiwa to Waimea.

The Waialua/North Shore area is currently used for several successful small farming vegetable operations, coffee, pineapple, seed corn operations, small ranching operations, and fallow. Assuming 25,000 acres (10,000 ha) of farmland were available, several options would be available. Working these lands in rotational crops utilizing a peanut-flax-peanut-rapeseed rotation, total oil yields over a two-year period would be approximately 10.1 million gallons (38.2 million liters) under ideal growing conditions with optimal yields. A one-year yield of jatropha with two fruiting and harvest cycles would provide approximately 15 million gallons (56.7 million liters) on the same-size parcel of land. Operational expenses would also be less, as fewer different pieces of machinery would be necessary. Climatic conditions in this region are favorable for production of most crops outlined in Section 3, save for oil palm, which could thrive with supplemental irrigation. Oil palm in this area could yield as much 19 million gallons (almost 72 million liters) per year using data from Table 2.

Suggestions of using more traditional oil crops such as soybean have been prevalent across Hawaii in recent years. To produce the necessary biodiesel to meet a B2 standard using a relatively low oil-containing crop such as soybean (~20% oil by weight) on Oahu would require nearly 34,300 acres (13,880 ha) of land, according to the previously made estimation that three crops could be grown in one year with total yields of 75 bushels per acre, or 105 gallons biodiesel produced from each acre. This practice would not be recommended however, as soybeans should be grown in rotation with other crops. Also, this would take significant amounts of prime farmland to attain these yields, and prime farmland is better utilized for food production, especially on densely-populated Oahu.

The Kunia district of former sugarcane and soon-to-be-former pineapple lands makes up an area of about 10,000 acres (4,050 ha). This land is used for seed (mostly corn) research and production, as well as truck crops and pineapple. The semi-arid conditions of this region dictate that a crop with good water conservation and nutrient utilization should be established for any oils production. Jatropha would make a good candidate capable of utilizing the wet season's rains for production of one crop, and using irrigation for a second yearly crop. This cycling would produce about 6 million gallons (22.7 million liters) of oils per year based on data contained in this report.

The leeward region east of Waianae and Nanakuli receives very little rainfall annually. Use of a drought tolerant crop is essential is leeward locations. Although it is considered a weed by many in the agricultural community, the ecology of castor bean is well-suited for such arid locations. Very little water is required to establish castor bean, and minimal amounts are necessary to sustain a crop. One year's yield of oil from castor bean on a 4,000 acre (1,620 ha) parcel of land would be approximately 1.1 million gallons (4.16 million liters), using information from Table 3.

As with Kauai's leeward locations, Oahu's Leeward Coast receives abundant sunlight and radiation year-round. The option of microalgae propagation and oils extraction should remain an option in the future. As technology is developed, especially by those at UH-Manoa, this may become more realistic. This options needs to be kept under consideration as the development of such a specialized endeavor may also provide other benefits to the state's leeward coasts' residents.

The North Shore area from Haleiwa to Waimea of old sugarcane lands would provide approximately 6,500 acres (2,600 ha) of land. Use of oil palm in these areas would maximize production on Oahu in higher-rainfall locations. Some supplemental irrigation may be required for such a crop, and use of more drought-tolerant varieties would be a possibility with an established breeding program. Using data taken from Table 2, this area could produce 4.9 million gallons (18.7 million liters) of oil per year.

The preceding scenarios, in combination, would supply Oahu with nearly 27 million gallons (102.1 million liters) of oil for biodiesel production. That is about one-seventh of Oahu's total diesel consumption of >180 million gallons in 2004. Ways to supplement this total would be to isolate available locations along the windward coast to implement small oil palm groves. It remains unlikely that Oahu will replace greater than 15-20% of its petroleum diesel with biodiesel, unless imports from other islands are pursued.

Jatropha and castor bean would not supply any livestock feed from by-products. Both jatropha and castor bean have toxic substances in their seeds. This fact does not diminish their usefulness as suppliers of high oil-content seeds with minimal inputs. The necessary transportation infrastructure is in place and available to producers who would wish to pursue such operations. The establishment of oil palm on Oahu would provide fodder for livestock. Each of these crops would require unique equipment for planting and harvesting. The necessary equipment for such operations would most likely need to be brought to the island. Oahu's highly-developed economy, shipping, and agricultural industry should provide all the resources any such operations would require.

7.4 Molokai

The island of Molokai did not have any specific locations outlined in Section 2.3. The Central and West Molokai districts are relatively uniform in their agricultural capabilities. Molokai's semi-arid climate and minimal available water for irrigation are the primary limiting factors for oil crop production.

Assuming an area of 15,000 acres (6,070 ha) was made available for biodiesel crop implementation, it would be possible for Molokai to replace its consumption of petroleum diesel with biodiesel. Installing jatropha on this land area would supply approximately 9 million gallons (34 million liters) annually with two harvest cycles per year. This would rely on seasonal precipitation for one cycle, and irrigation would be required for the second. If only one fruiting cycle were desired, the wet season's rains would supply enough moisture for one crop. The 4.5 million gallons (17 million liters) produced from that single harvest would replace most, if not all, of Molokai's petroleum diesel.

Molokai's climate would also support potential tree crops such as pongam, or annual crops such as castor bean, jojoba, peanut, flax, or sunflower. Isolation of highest returns for inputs should be considered on Molokai. Resources are not as readily available as on more populated islands. The presence of coffee on Molokai should encourage pursuit of a crop like jatropha that may utilize equipment which can be used by multiple operations. In addition, Jatropha requires minimal water once established so it should not compete with the existing agricultural uses such as coffee, seed production and truck crops. The rural areas on Molokai make transportation of harvested crops a minor concern, but with proper planning, any infrastructure issues should be addressable. Molokai's production could potentially be great enough to export biodiesel to neighboring islands, particularly Maui.

7.5 Lanai

Lanai has only one location suitable for biodiesel crop implementation. As discussed in Section 2.3, the Central Plateau has approximately 12,000 acres (4,860 ha) of land suitable for crop production. Conditions of this area are briefly discussed in that section.

If the 12,000 acres were used to produce jatropha in the absence of irrigation, annual yields would be approximately 3.6 million gallons (13.6 million liters) of oil. It is believed that this total of biodiesel would be sufficient to supply Lanai's necessary electricity needs and transportation requirements. Specific data on Lanai's consumption of petroleum diesel must be consulted. Other crops that may be able to produce substantial amounts of oil in the arid climate with little to no supplemental irrigation are jojoba, castor bean, and pongam.

Potential crops on Lanai are limited as water is a very limiting factor. Availability of equipment, labor, fertilizer, and suitability of infrastructure are also concerns. A detailed production plan would need to be developed if the landowner is interested. Lanai may have the potential to supply enough biodiesel to ship excess supplies to neighbor islands.

7.6 Maui

Maui consumed over 22 million gallons (83.2 million liters) of petroleum diesel in 2004. As the base of operations for Pacific Biodiesel, Maui's energy and transportation sector have significant previous exposure to biodiesel products. Available land on Maui is detailed in Section 2.2. Other lands may be available for biodiesel crop implementation in the future.

The leeward side of Maui near Lahaina and other coastal areas once used for sugarcane encompasses an area of over 6,000 acres (2,425 ha). Limited portions of this land are currently used for coffee and seed corn production. If an area of approximately 4,000 acres (1,620 ha) were established in jatropha at this site, nearly 2.5 million gallons (9.5 million liters) of oils would be produced on site with two harvests per year. With semi-arid conditions, the use of drought-tolerant crops is ideal. However, supplemental irrigation would be necessary to produce this volume. Other crops with potential at this site are castor bean, jojoba, or a rotational system utilizing peanuts-flax-castor bean and other oil-producing annual crops. Any species used with toxic properties would limit the use of by-products to organic fertilizer and solid fuels.

Lands along the eastern and southern slopes of Mt. Haleakala, south of Pukalani and below Kula, are comprised of marginal crop land. Portions of these lands are used for small specialty operations, nurseries and greenhouse crops, ranching, and other miscellaneous purposes. An area of land covering 20,000 acres (8,100 ha) could produce significant amounts of biodiesel for Maui. With rainfall totals ranging from 20-40" per year, more than one crop may be implemented in this region for biodiesel purposes. Because soil and water runoff can be significant on mountain slopes, utilization of tree crops that require few soil disturbances is ideal. In drier areas, jatropha could be grown and supplemented with seasonal irrigation to produce two harvest periods per year. In moist areas, kukui would provide a high volume of oils while providing aesthetic beauty along Mt. Haleakala's slopes. By splitting these 20,000 acres into two equal parts, one in jatropha and one in kukui, total yearly production for this region could exceed 12 million gallons (45.4 million liters) of oil for biodiesel.

The two locations discussed in this report for Maui could supply over 14 million gallons (53 million liters) of biodiesel to Maui's economy, which is more than 50% of the total of petroleum-based diesel consumed on the island in 2004. Access to these two locations may be limited by current operators on those lands. Other areas on Maui could be used, but current lands in sugarcane, pineapple, and ranches already feel pressures from expanding residential areas on the island. Development pressures are expected to be the most-limiting factor for oil crop production on Maui, and access to water will be a growing problem in the short- and long-term. The agricultural lands near Hana could provide an area to utilize oil palms to supply high volumes of oil for biodiesel production, but the transportation infrastructure connecting the windward side of the island to its population centers is a concern. Similar concerns exist for lands located on some other slopes of Haleakala.

7.7 Hawaii

The Big Island offers the greatest potential for high-volume production of biodiesel of any island in the State. As outlined in Section 2.5 the Big Island has many areas for potential placement of oil crops. Three specific areas were detailed in Section 2, but other locations should be considered as well if access were granted by interested parties. The three areas detailed in Section 2 (Hamakua Coast, Puna District, and Ka'u District) could supply enough oil for biodiesel processing to supply all of the Big Island's needs, as well as supplementing the needs of other islands.

The lands along the Hamakua Coast north of Hilo are currently forested with commercial plantings of *Eucalyptus sp.* trees. These lands have been forested since the decline of the sugar industry on Hawaii. Once these forests are harvested, the climate and soils of this region would permit a large-scale operation utilizing oil palm to produce oils for biodiesel. An area approximately 50,000 acres (20,200 ha) in size could produce nearly 38 million gallons (143.8 million liters) of oil, almost enough to meet 2004's island-wide usage of 40 million gallons (151.4 million liters). This area receives 60-150" of rainfall per year, based on information from Section 2.5, and it is expected that no supplemental irrigation would be necessary. Field access would be similar to that used by the old sugar plantations and forestry operations. As oil palms matured, the understory could be managed for other crops to provide a dual use of the land.

The Puna District is made up of old sugarcane lands, papaya operations, nurseries, and other small operations. If the area known as the 'Puna Rocks' were to be converted into an oil palm agro-forestry operation, a 70,000 acre (28,350 ha) parcel could produce approximately 53 million gallons (200.6 million liters) of oil for biodiesel annually, using figures from Section 3.6. With annual rainfall averaging 90-200" per year, no irrigation would be necessary. Because of the shallow soils of the region, utilization of organic residues from the trees would be of great importance. The oil palms would serve as soil-builders while supplying a high volume of oils.

An area of approximately 25,000 acres (10,100 ha) in the Ka'u district on the southern portion of Hawaii could be placed into agroforestry operations. With average annual rainfall ranging from 30" to 80", the use of more than one crop should be considered. In lower rainfall areas (those areas receiving less than 50" per year), plantings of kukui trees could supply over 4.5 million gallons (17 million liters) of oil on half of the area. If the remaining 12,500 acres were used in oil palm, that would supply another 9.5 million gallons (35.9 million liters) of oil. The use of tree crops for oil production would take advantage of the rocky conditions, and their organic residues would aide in soil-building.

Potential yields from these three regions of the Big Island would provide over 100 million gallons (378.5 million liters) of oils for biodiesel production. That would make approximately 60 million gallons (227 million liters) of oil for fuel available for export to other islands with unfulfilled fuel needs, based on 2004 data. There are other potential areas for biodiesel crop implementation on Big Island, and production there could potentially be even greater than the totals described above. A major component of biodiesel production on Hawaii would be the market for livestock feed. With large ranching operations in place, Big Island could utilize large volumes of high-quality feed for finishing cattle to sell in local markets. Exporting large volumes of biodiesel to other islands is possible and is safer than petroleum-based diesel. Interisland transportation economics will need to be evaluated.

8. Conclusions and Recommendations

Over time it is reasonable to expect that Hawaii could produce enough agricultural biodiesel to reduce imported diesel by 20%. All diesel could be a blend of B20, decreasing emissions of greenhouse gases, sulfur oxides in particular, and supplying Hawaii's economy with more agricultural jobs. With the current knowledge, it should not be expected that Hawaii can produce enough biodiesel to completely abandon the need for petroleum-based diesel. Based on figures from Section 7, if the suggestions for the various islands from this report were put into practice, and expected yields were attained, Hawaii could potentially produce more than 150 million gallons of biodiesel per year. That is the equivalent of over 16.5 million barrels (assuming one-fifth of a 42-gallon barrel is utilized for diesel fuels) and more than 55% of the total diesel usage of roughly 263 million gallons for the State in 2004.

There is little history of oil crop production in Hawaii, and the only vegetable oil-producing plants that have been utilized in the past have been done so sparingly, including kukui, coconut, avocado, soybean, sunflower, flax, and algae. The work that has been done with oilseed crops has not been well-documented, and work done around the world with tropical oilseed crops seems to have many omissions of crop specifics along with declarations of 'miracle plants' that can meet fuel needs of entire nations.

It is recommended that because of the current lack of crop selection and its production requirements and the lack of infrastructure for alternate fuels that a biodiesel implementation program be approached methodically and cautiously. Determining which crop(s) will be the most viable, which production protocols to use and which business model(s) are practical for Hawaii's future are important first steps to implement a sustainable biodiesel agricultural industry.

There have been small test plots of traditional oilseed crops such as soybean and sunflower across the islands over many years. Much of this data suggests that the mainland traditional oil crops may not be the direction to take in regards to Hawaii's situation. However, there are several crops that may be viable options for oilseed production in Hawaii.

Pursuing selected advanced germplasm of potential crops, such as palm oil and jatropha developed by international research and governmental organizations needs to be considered to avoid decades of local development for an oil crop suited to Hawaii's multiple environmental niches.

The African oil palm is the best known source for vegetable oil and the highest oil producing plant in the world. Considerable work has been done with this plant in other island environments and Hawaii should be able to benefit from these efforts in determining its use as an oil crop in its islands. It is well suited to wet windward environments. Considerable germplasm development has already occurred and might be available for testing here. Harvesting presents some challenges and engineering solutions will be needed.

The tropical plant *Jatropha curcas* is the type of oilseed bearing plant that can withstand less than optimal growing conditions, and it can produce up to three harvestable crops per year with minimal irrigation requirements. It is well suited to arid leeward environments. Less is known about germplasm development/adaptation of this plant. However, what is known is that it does not need premium farmland, it can be grown on marginal soils and it can be harvested mechanically with minimal amounts of engineering needed. Mechanical harvesting of jatropha would be limited to lands where rocks and slopes are not major limiting factors. Because jatropha is non-native, work should be done in controlled settings to ensure the plant will not become invasive.

Other plants that may have potential for significant oilseed production in Hawaii are peanut, flax, castor bean, jojoba, kukui, *Pongamia pinnata* (Pongam tree), Chinese tallow tree, and *Moringa oleifera* (Ben-oil tree). Culled avocados on each island could also be collected for oils extraction to contribute to an existing biodiesel production. Each of these plants needs further evaluation, as each could provide significant amounts of biodiesel on a per acre basis. Of the other crops detailed within this report, one of the most-promising is algae. Although much work remains to be done in isolating strains of microalgae, engineering the production systems, and perfecting the harvesting of oils within the algae, the sheer volume of extractable oils that could be processed from one acre of algae ponds make them worth considering. Because Hawaii's climate is nearly perfect for algal cultivation, this option should not be ignored, regardless of the size of the investment. Many of the traditional row crops outlined in Section 3, i.e., soybean, rapeseed, and sunflower should not be entirely ruled out for particular situations, but their oil production per unit land area currently is not as favorable as the other crops proposed.

It is also recommended that research goals and objectives be established to provide the necessary support for a new agricultural sector, crop biodiesel production.

If biodiesel does become a significant source of liquid transportation fuel and is used for other industrial applications, it will serve as a bridge to becoming less dependent on non-renewable energy sources. In situations where marginal agricultural lands can be utilized by converting them to extremely hardy and resilient oil crop species, it could be possible to continue producing such crops indefinitely and provide the land with a productive agricultural use.

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