Scott Q Turn

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May 1995

HAWAII NATURAL ENERGY INSTITUTE
School of Ocean and Earth Science and Technology
University of Hawaii at Manoa

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Contents

Abstract

Pursuant to mandates issued by the State of Hawaii Public Utilities Commission requiring that Hawaiian Electric Company develop an integrated resource plan for electric power generation in Hawaii, the potential to generate electricity from biomass on the island of Oahu was investigated. Key technical and economic factors, such as land suitability and availability, energy-crop yield, delivery cost, and potential quantities and costs of electricity generated, were examined for a model production unit, Waialua Sugar Company (WSCo).

Banagrass, a variety of Napiergrass (*Pennisetum purpureum*), is a promising crop species for conversion into electricity. Lands presently planted in sugarcane at WSCo have adequate supplies of irrigation water, and terrain, soils, and climatic conditions that are highly suitable for banagrass production. In addition, unit operations associated with the cultivation of banagrass are expected to be similar to, but less costly than, corresponding sugarcane cultivation operations. The ability to produce high-yielding ratoon crops (i.e., regrowth following harvest), integration of seed-cutting and crop-harvesting operations, and utilization of standardized mechanical harvesters and moderately-sized transportation systems would result in lower soil preparation, seed production, planting, and weed control costs than for sugarcane. Moreover, the potential for high commercial yields of banagrass (projected to be about 21.5 tons/acre-year), and for increasing yields further by implementing aggressive yield-improvement practices, make banagrass an ideal energy crop. In light of the abovementioned factors, banagrass appears to be the most suitable species for dedicated-biomass-for-electricity production at WSCo and, thus, was selected for analysis in this investigation.

The estimated cost of producing banagrass feedstock, FOB conversion-facility gate, is approximately $60 per ton, dry basis (see following table). Roughly 30% of the delivered cost of banagrass is attributable to harvesting and transportation, combined; an additional 30% of the delivered cost is due to various indirect factors that support biomass production including crop control, road maintenance, general and administrative functions, and peripheral field operations. Within the major cost centers — soil preparation and planting, irrigation, fertilization, harvesting, and transporting — and in general and administrative functions, there appear to be sufficient opportunities for cost reduction (particularly in the form of higher worker productivity than assumed in this analysis) so that the cost of cultivating and delivering banagrass to the conversion facility can be reduced by ~10% (to ≤$55 per ton). Increasing crop yield and/or increasing the number of ratoons obtainable from a single plant crop can significantly reduce the unit cost of landing banagrass feedstock at the conversion facility. It is estimated that increasing banagrass yield by 10% would decrease the delivered cost by a comparable amount, and that increasing the number of ratoon crops per plant crop from five (the number assumed in this analysis) to eight would reduce the feedstock cost by more than 7%.

Approximately 20 MW of electricity could be generated from banagrass in WSCo's moderate-pressure cogeneration facility by replacing the existing turbogenerator and condenser to accommodate reduced extraction. However, because the existing boiler system at WSCo has a relatively low pressure rating, the overall conversion efficiency would be rather low, ~13%. Medium-pressure steam generation and biomass gasifier/gas-turbine combined-cycle systems (the latter of which still needs to be demonstrated in an integral fashion) are judged to be logical

alternatives to the existing cogeneration unit at WSCo. Biomass-energy-to-electricity conversion efficiencies for those two alternative systems are estimated to be 25% (1140 kWh/ton) and 31% (1420 kWh/ton), respectively. With processing plant and conversion facility parasitic requirements deducted, 36 MW of electricity would be exportable from the medium-pressure steam generation system and 46 MW from the gas-turbine based combined-cycle system. On those bases, 280 to 350 million kWh of electrical energy would be exportable annually.

Although not part of the original scope of this investigation, an attempt was made to project the cost of generating electricity from biomass feedstock produced at WSCo. Given the higher efficiency, moderate developmental risk of the technology, and relatively short lead time anticipated for commercialization, only the gas-turbine based system was considered in the electricity generation cost analysis attempted here. For a gas-turbine based combined-cycle system operating at a conversion efficiency of 31% and feedstock cost of $60.45 per ton, approximately 350 million kWh of electrical energy (at a delivery rate of 46 MW) would be exportable from 12,000 acres of banagrass produced at Waialua. The cost of electricity from a gas-turbine based system is projected to be $0.101 per kWh, comprising $0.044 per kWh to grow and deliver the feedstock, and $0.057 per kWh to convert the feedstock into electricity. Although the cost of installing and operating a conversion plant conceivably might be lower using less efficient technologies, any resultant cost savings in biomass-to-electricity conversion must be weighed against likely increases in the apparent cost of the fuelstock owing to reduced conversion efficiency. If the conversion efficiency can be increased beyond that assumed in this analysis, then the apparent cost of the fuelstock would decrease commensurately, likely resulting in less costly exportable power. It is important to note that application of renewable energy production credits, accelerated depreciation factors, and other incentives presently being considered by the federal government for closed-loop biomass energy systems could improve the economic feasibility of generating electricity from banagrass. Potential credits associated with sewage handling (presently being pursued by WSCo) and reduced emissions could further improve the economics of biomass-for-electricity production. Combined, these credits could reduce the effective cost of producing banagrass and converting the biomass into electricity by >$20 per ton of banagrass produced or >$.02 per kWh of electricity exported. However, such potential savings would be partially offset by costs not included in this analysis such as land rent, and feedstock handling and dewatering costs, which could add >$5 to each ton of banagrass produced.

A potential problem for banagrass-fired power generation systems is ash deposition. Analyses indicate that ash in banagrass contains high levels of potassium, chlorine, and silicon — elements known to promote ash deposition in combustion systems. Ash deposition and agglomeration can degrade boiler performance by reducing heat transfer, accelerating corrosion, and restricting flow through the boiler. Because banagrass ash contains much higher levels of potassium than sugarcane bagasse, the firing of banagrass in a boiler unit may pose a high slagging risk. Many of these concerns relating to steam-based power generation systems also would apply to advanced gas-turbine based systems. Therefore, additional testing is strongly advised to determine the slagging potential of banagrass and to evaluate the effectiveness of feedstock pretreatment alternatives, such as leaching, in removing water soluble alkalis.

Favorable social, environmental, and energy-policy impacts should accrue from the production of banagrass and its subsequent conversion into electricity in Hawaii. Combined field and conversion-facility operations for a dedicated banagrass-for-electricity establishment at WSCo could produce over 200 employment opportunities for the north shore of Oahu; an equal or greater number of indirect jobs would accrue to support this direct labor force. With regard to the environment, photosynthetic uptake of carbon dioxide by the growing banagrass makes this electricity-generation option carbon neutral; soil disturbance and erosion are expected to be lower with banagrass than with sugarcane; and with the adoption of appropriate mitigation strategies, negative impacts on the environment should be negligible. Additionally, expanded biomass power generation in Hawaii would help the State reduce its reliance on imported fossil fuels.

Summary of banagrass production costs per acre harvested, per cultivated acre-year, and per ton harvested (dry basis), by cost center.

	$/acre harvested			$/acre-year[b]	$/ton[c]
Cost Center	Plant	Ratoon	Average[a]	Average	Average
Soil Preparation/Planting	551	0	92	138	6.41
Seed Production	78	0	13	20	0.91
Weed Control	225	23	56	85	3.94
Irrigation	82	82	82	123	5.74
Fertilization	105	105	105	158	7.36
Harvesting	146	146	146	219	10.22
Transporting	118	118	118	177	8.26
Road Maintenance	11	11	11	16	0.74
Crop Control/Research	28	10	13	20	0.93
Other Field	132	49	63	94	4.37
Equipment Shop	53	20	25	38	1.76
Landholding	0	0	0	0	0.00
G&A—Field	296	109	140	211	9.81
Subtotal—Field	1827	673	865	1298	60.45

a Assumes each plant crop is followed by five ratoon crops.
b Average age at harvest assumed to be eight months.
c Average yield assumed to be 21.47 tons/acre-year.

1. Introduction

1.1. Background

In March 1992, the State of Hawaii Public Utilities Commission issued a series of orders requiring that Hawaiian Electric Company (HECO) develop an integrated resource plan (IRP), to be updated on a three-year cycle, which considers all supply- and demand-side electricity resource options appropriate for Hawaii, and develop a program implementation schedule for the IRP. In pursuing the initial phase of the IRP, HECO and its consultants performed preliminary and final screenings of the options available for Hawaii to eliminate those options that were not feasible. Various non-fossil-fuel energy options were examined by HECO: geothermal, hydroelectric, biomass, wind, solar thermal, nuclear, ocean energy, and photovoltaic. Biomass energy was found to have a technological base and typical generation-unit size that could contribute significantly to the electrical requirements of the utility company (including on the island of Oahu) as well as match the utility's needs for incremental blocks of generating capacity.

To that end, HECO pursued more detailed biomass resource assessments for the islands of Hawaii, Maui, and Oahu. This report describes the analysis performed for the island of Oahu as a part of HECO's IRP Action Plan. To make the investigation most meaningful, HECO requested that this effort take the form of a case study. To that end, this investigation examines a single production unit, Waialua Sugar Company (WSCo), using largely information collected by the University of Hawaii's Hawaii Natural Energy Institute (HNEI) and the Hawaiian Sugar Planters' Association (HSPA) in previous projects as well as data supplied by WSCo.

1.2. Approach

This investigation was organized along three major thrusts:

- Delineation of lands at WSCo available and suitable for dedicated biomass-for-energy production;
- Projection of energy-crop yields and costs of delivering the crop to a central feedstock-conversion/power-generation facility;
- Determination of the potential amount of electricity producible from dedicated biomass feedstocks and the cost of generating electricity.

This report is organized along the same thrusts: Chapter 2 provides a general description of WSCo and some details pertinent to assessing the yield potential of energy crops grown on that plantation; Chapter 3 describes the energy-crop species selected in the screening process and provides yield projections for that species; Chapter 4 describes the cultivation, harvesting, and transporting sequences for the selected energy crop and projects costs associated with those operations; Chapter 5 summarizes the properties of the energy crop and estimates of the amount and cost of electricity producible from that crop. Chapter 6 summarizes the findings of this investigation.

2. Description of Waialua Sugar Company

2.1. General Description

Waialua Sugar Company, located near the north shore of the island of Oahu (Fig. 2-1 and Fig. 2-2), has been in operation since 1899 (initially as Waialua Agricultural Company, with chief investors Castle and Cooke, and B.F. Dillingham), although portions of the land farmed by WSCo were planted in sugarcane prior to 1840 under different ownership (Star Bulletin, 1935). Following its first sugarcane crop in 1899, which yielded 1700 tons of sugar from 300 acres, WSCo grew to become one of the larger sugar producers in the State, reaching peak production in the mid 1970s of approximately 80,000 tons of sugar per year. In the six years preceding its November 1994 announcement to cease operations at the end of the 1996 campaign, WSCo averaged nearly 60,000 of sugar annually, from ~5300 acres harvested per year, off 12,000 cultivated acres (Fig. 2-3). Approximately one-half of the 12,000 acres that it farms is owned by WSCo; the other half is owned by the Bishop Estate.

Sugarcane is grown on more than 120 fields at WSCo, varying in size from <10 acres to >300 acres (averaging ~100 acres), labeled according to the general location of the field (Fig. 2-2); these include large tracts in the northeastern section of the plantation, Waimea, Kawailoa, Opaelua, and Helemano, and smaller tracts in the southwestern section, Paalaa, Mill, Valley, Kemoo, Ranch, Gay, and Kawaihapai. The eastern section of WSCo is bordered by pineapple grown by Dole Fresh Fruit Company. Because of the close proximity of the sugarcane and pineapple operations, and because both agricultural entities, WSCo and Dole Fresh Fruit Company, are subsidiaries of the same parent company (Dole Food Company), the line of demarcation between sugarcane and pineapple has drifted back and forth over time.

Roughly 85% (~10,400 acres) of the caneland at WSCo is irrigated; the remaining 15% (~1600 acres), mostly in the northeastern section of the plantation, is unirrigated. Yields of cane and sugar vary throughout the plantation (Fig. 2-4), being highest in drip-irrigated fields in the northern section, lower in the southwestern section irrigated by millwater (i.e., the effluent from the sugar factory's cane-cleaning plant), and lowest in the northeastern, unirrigated fields.

General descriptions of the present agronomic conditions at WSCo, including climatic, topographic, soil, and water characteristics, are presented in the following sections. Because the availability and suitability of irrigation water is critical to the viability of energy-crop production, water is given more detailed treatment than the other agronomic factors.

2.2. Agronomic Conditions

2.2.1. Climate

The island of Oahu has a mild, subtropical climate, with minimal variation in seasonal temperature. Seasonal temperatures rarely exceed ±10°F of the mean annual sea-level temperature of 75°F; mean temperatures (71 to 75°F) decrease approximately 3°F for every 1000-foot increase in elevation (University of Hawaii, 1972).

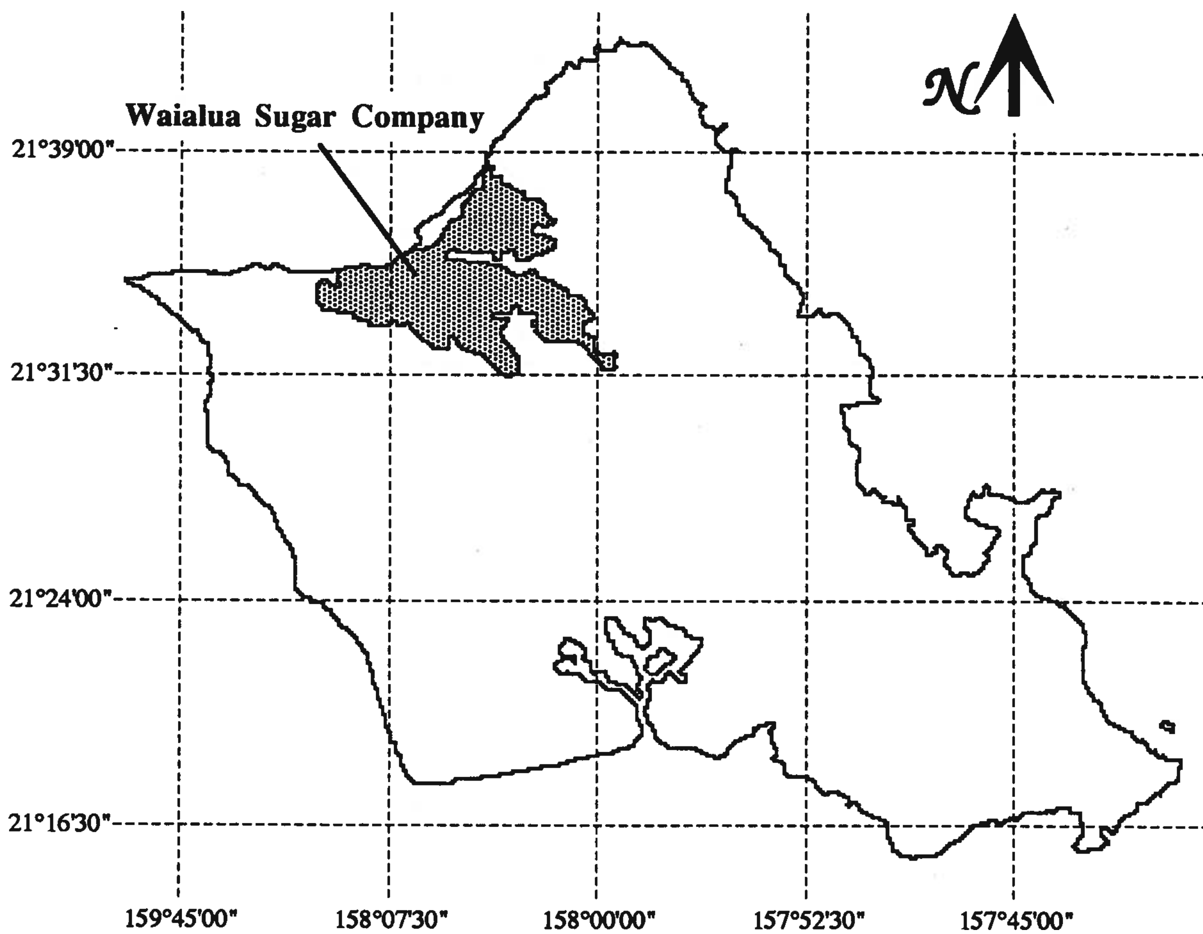

Fig. 2-1. Waialua Sugar Company, island of Oahu.

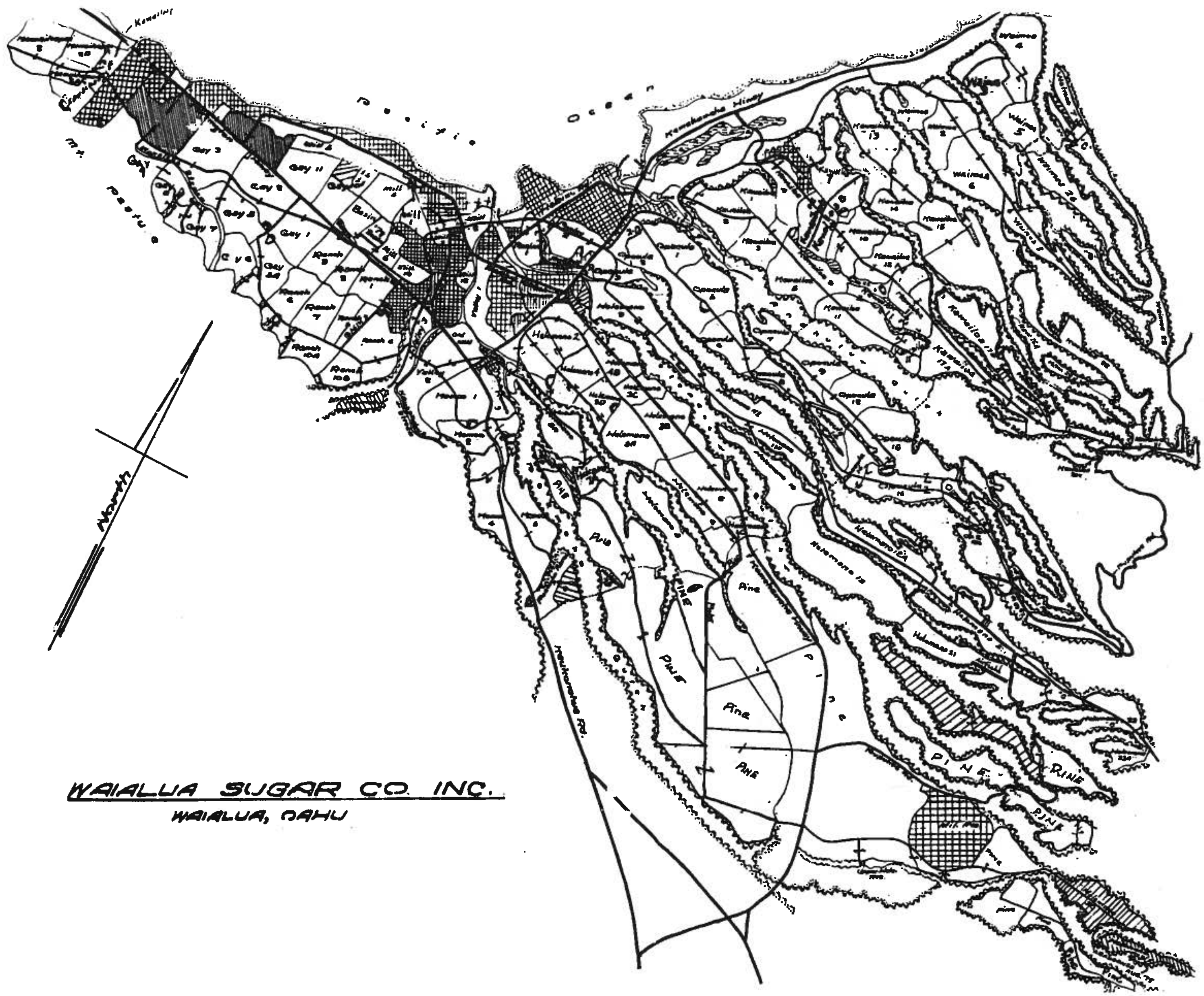

Fig. 2-2. Waialua Sugar Company, sugarcane field designations, and surrounding pineapple fields.

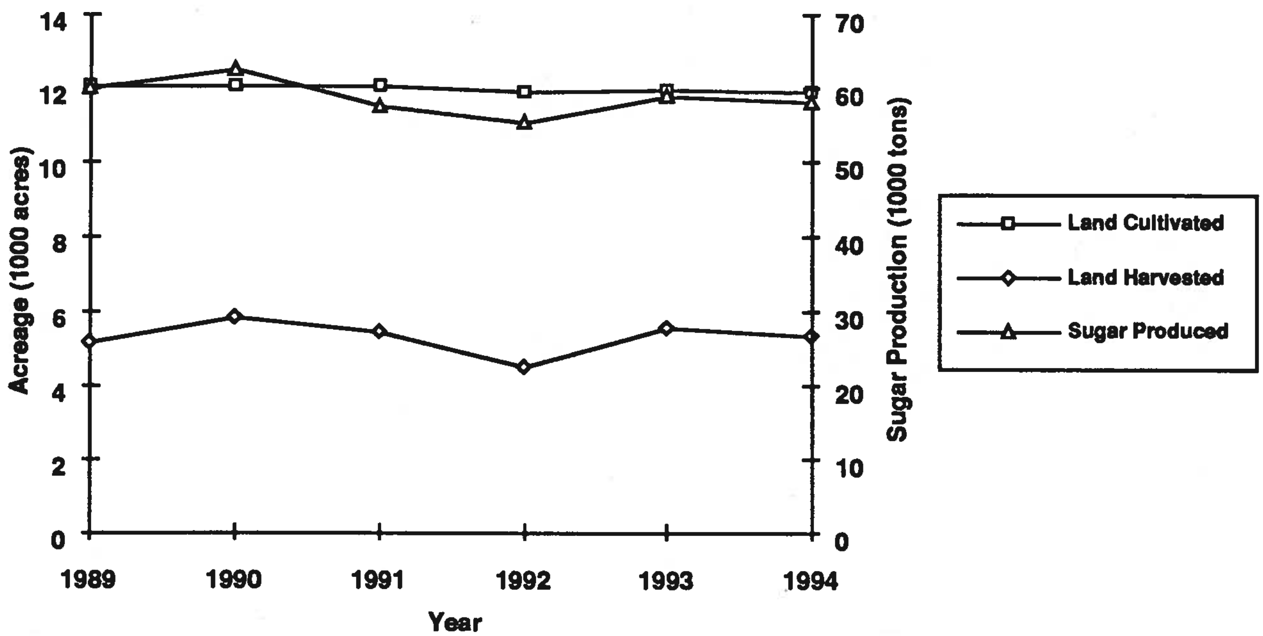

Fig. 2-3. Acreage cultivated, and acreage harvested and sugar produced annually at WSCo, 1989–1994.

The median annual rainfall for agricultural lands farmed by WSCo ranges between 15 and 60 inches (University of Hawaii, 1972). The majority of lands south of Helemano Stream have a median annual rainfall between 15 and 40 inches, while lands north of Helemano stream and south of Kawailoa Stream receive annual rainfall in the range of 25 to 60 inches. Since high-yielding energy crops require water application rates exceeding 100 inches per annum, it is most likely that the vast majority of the land presently farmed by WSCo would need to be irrigated to produce commercial yields of energy crop.

Agricultural lands used by WSCo receive relatively high insolation rates of 460 to 525 langleys (calories/cm^2-day), with inland areas having lower insolation rates than coastal areas. Provided that adequate water supplies are available, high insolation rates translate to high crop yield.

2.2.2. Topography

Lands with slopes below 10% are more suitable for agriculture than steeper terrain because irrigation, mechanical cultivation, and harvesting can be performed with less difficulty. The majority of lands farmed by WSCo have slopes below 10%; a few areas, generally farther inland and closer to the Koolau mountain range (north of Helemano Stream), have slopes between 11 and 20% (University of Hawaii, 1972). Because the equipment anticipated for cultivating and harvesting biomass energy crops are similar to those presently in use at WSCo (see Section 4), field equipment for energy-crop production should not have much difficulty negotiating the terrain upon which sugarcane is presently being grown at WSCo.

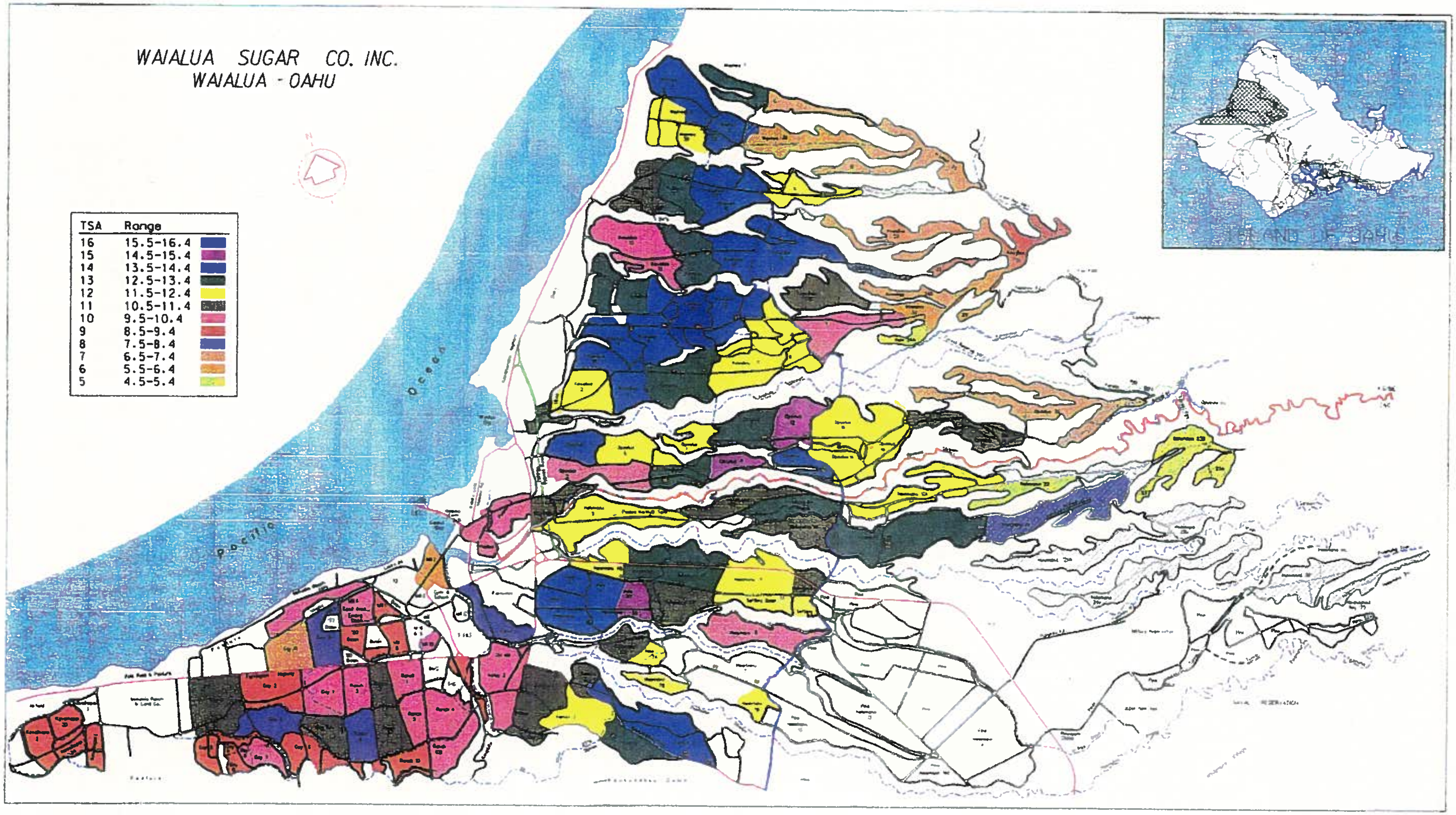

Fig. 2-4. Average sugar yield (tons sugar/acre per crop), by field, at WSCo.

Lands cultivated by WSCo have two major elevation classifications. Lands south of Helemano Stream are relatively low lying (<300 feet in elevation). In general, lands farther from the coastline increase in elevation, ranging between 150 and 1200 feet. Numerous reservoirs are located at higher areas having elevations approaching 2000 feet. (University of Hawaii, 1972); therefore, most of the biomass crops can be irrigated with water supplied by gravity from higher-lying reservoirs. Locations of high-elevation reservoirs, mostly in the Opaeula and Kawailoa sections, are shown in Fig. 2-5.

2.2.3. Soil

Soil classification presently is described according to six different categories: order, suborder, great group, subgroup, family, and series. In this report, soils in the Waialua-Haleiwa area will be classified by order, the highest category of classification, and by series, the most specific category of classification. Order is based on diagnostic horizons, or special features that characterize the soil forming processes, and upon morphology. Series relates to the characteristics of the soil below the plow plane.

Lands farmed by WSCo fall into four different soil orders: (1) Alfisols, (2) Vertisols, (3) Mollisols, and (4) Entisols. The soil order profile of the Waialua-Haleiwa area has been reported by McCall (1973). Alfisols, Mollisols, and Entisols generally are suitable for agriculture; Vertisols require greater soil management to be suitable for agriculture.

The coastal area extending from Mokuleia to Waimea have soils of the Entisols order. Entisols are soils with little or no horizon development, and can be formed from any type of parent material. Entisols are used in agriculture; however, their suitability depends on location, water supply, texture, and accessibility (McCall, 1973).

The majority of the lands extending inland, adjacent to the aforementioned coastal region, are classified as Mollisols. Soils in a smaller tract of land lying east are of the Vertisols order. Mollisols are deep (>30 inches) soils, having granular or crumb-like structures, and are fine- to moderately-fine-textured, and well-drained. These soils, high in base saturation, are dark or red in color with a mollic epipedon high in organic matter. Mollisols have good natural fertility (varying with weather conditions) and do not harden when dry; therefore, they are excellent for agriculture (University of Hawaii, 1972). Vertisols, on the other hand, have poor structure and tend to crack severely during dry periods. In addition, the shearing and shrinking characteristics of these soils make them less suitable for farming and infrastructure development (United States Department of Agriculture Soil Conservation Service, 1972).

Soils farther east and immediately south of the areas containing Mollisols and Vertisols are classified as Alfisols. Alfisols, red in color with moderate to high base saturation, are characterized as having an accumulation of clay in the subsurface. These mineral soils are known to be capable of storing sufficient moisture to sustain plant growth for three months or more, and if irrigated, they can be highly productive (McCall, 1973).

A recent soil survey identified 22 different soil series on lands farmed by WSCo. The names and locations of these soil series are presented in Fig. 2-6. The two most prominent soil

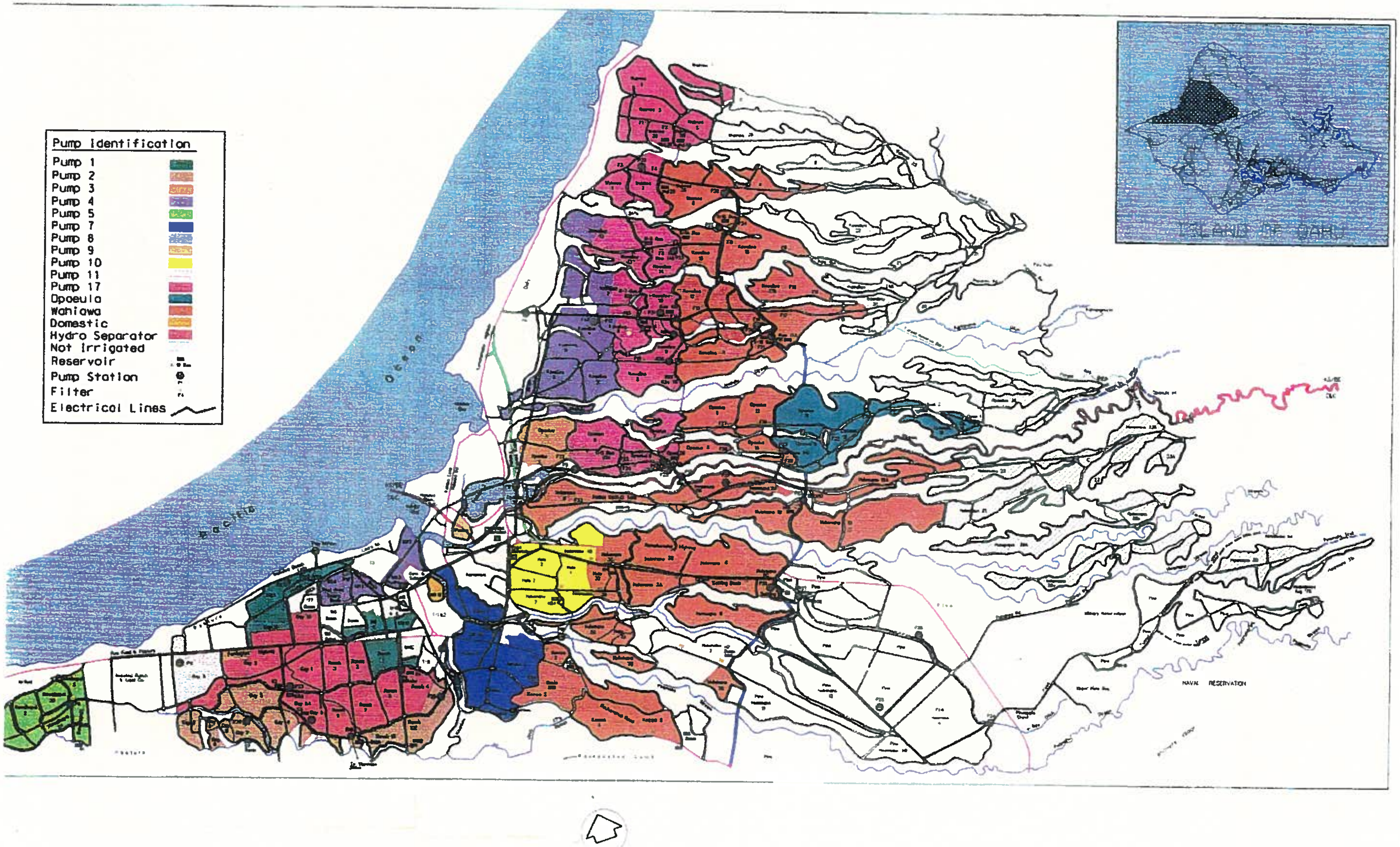

Fig. 2-5. Water distribution system, by pump or source, at WSCo.

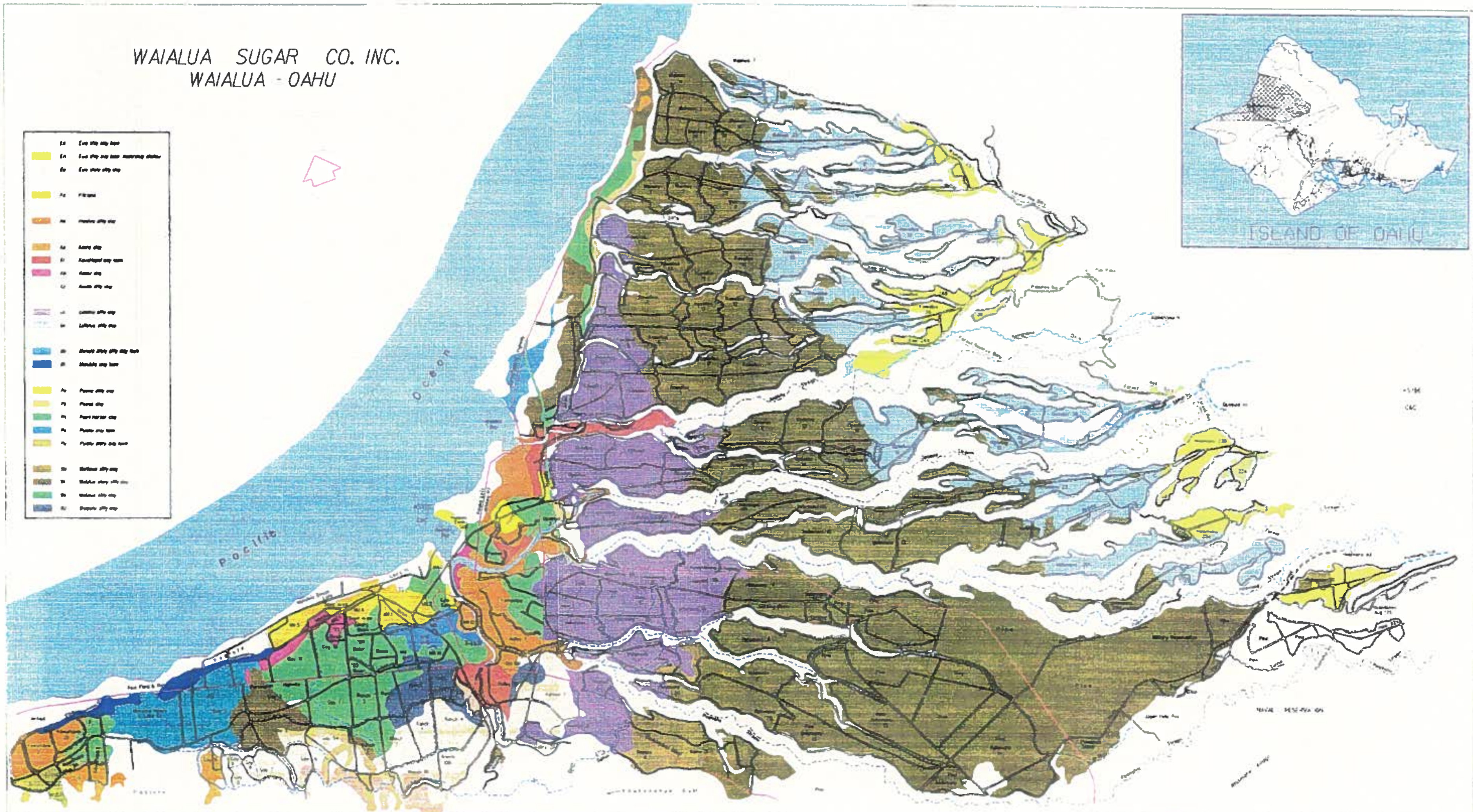

Fig. 2-6. Distribution of soil types at WSCo, by soil series.

series are the Lahaina and Wahiawa silty clays. Lahaina silty clays are characterized as having moderate permeability, slight to moderate erodability, and slow to medium runoff. These soils have medium acidity and 1.3 inches per foot of available water capacity in the surface layer, and slight to medium acidity and 1.4 inches per foot of available water capacity in the subsoil (United States Department of Agriculture Soil Conservation Service, 1972). Wahiawa silty clays have moderately rapid permeability, slow to medium runoff, and slight to moderate erodability. Available water capacities and acid levels are comparable to Lahaina silty clays; however, the subsoil may be neutral in acidity.

2.2.4. Water

Roughly 85% (10,400 acres) of the 12,000 acres of caneland at WSCo is irrigated by a water distribution system that is considered to be one of the best in the Hawaiian sugar industry (Fig. 2-5). Waialua Sugar Company obtains water from Wahiawa Reservoir (Wilson Lake) and from several catchment and reservoir systems (Helemano, Opaeula, and Kawailoa). Wahiawa Reservoir is operated by Wahiawa Water Company, a wholly owned subsidiary of WSCo's parent company, Dole Food Company. Approximately 7350 acres (~70% of the irrigated acreage) are irrigated with Wahiawa mountain water containing sewage effluent.

Sewage effluent discharged into Wahiawa Reservoir is treated to the secondary level, which calls for the removal of solids and harmful bacteria (beneficial bacteria are left in to break down the waste water). Waialua Sugar Company's use of water in the reservoir is crucial to the lake's viability, since the withdrawal of water for irrigation helps to stir-up and flush nutrients. Significant reduction or ceasing of this practice may disrupt the nutrient balance of the reservoir (Infante, 1993). Approximately 95% of the lake's nutrients comes from sewage effluent discharged into the reservoir. It has been projected (Waialua Sugar Company, 1994) that if sewage effluent increases proportionately with population (which is projected to increase by 46% between 1980 and 2010), the amount of discharge from the Schofield Wastewater Treatment Plant will increase to 3.9 million gallons per day (from 2.7 million gallons per day) and the amount from the Wahiawa Wastewater Treatment Plant will increase to 2.9 million gallons per day (from 2.0 million gallons per day). Both the military (Schofield Wastewater Treatment Plant) and the City and County of Honolulu (Wahiawa Wastewater Treatment Plant) have easement agreements which allow for discharging into Wahiawa Reservoir. The military pipeline easement, established in 1978 and amended for seven years, beginning January, 1995, provides compensation to Wahiawa Water Company for access to the reservoir; the City and County easement, established in 1929, is perpetual, and presently does not provide any compensation for access to the reservoir.

Treated sewage effluent, used in conjunction with ditch water, has been used to irrigate sugarcane fields in Hawaii for many years. Increased cane yields have been documented when the combined water resource is managed effectively. Nutrient analyses of the effluent from Wahiawa Sewage Treatment Plant and of the water at the irrigation withdrawal in the Wahiawa Reservoir are summarized in Table 2-1. It should be noted that the data in Table 2-1 are averages of select measurements taken over a five month period. Detailed nutrient analyses for raw sewage from the Mililani Sewage Treatment Plant and for cane irrigation effluent are provided in Table 2-2.

Table 2-1. Nutrient concentrations at South Fork of Wahiawa Reservoir (Schmitt, 1973).

Location	Nitrogen, mg-N/L NO_3+NO_2	NH_4	Organic	Total	Phosphorus, mg-P/L Soluble
Treatment plant effluent	0.48	21.7	0.51	22.7	2.04
Irrigation withdrawal	0.35	0.49	0.08	0.92	0.15

Table 2-2. Nutrient concentrations in raw sewage and chlorinated effluent from Mililani Sewage Treatment Plant (Ekern, 1975).

Constituents, mg/L	Raw Sewage (median)	Irrigation Water (mean, 6/73-12/73)
Dissolved Solids	307	–
Settleable Solids	6.5	–
Suspended Solids	178	–
Grease	64.4	–
BOD	204	–
COD	470	–
Chloride	75	56
Sulfate	64	39
Boron	0.46	–
Silica	30	69.5
Nitrite-N	0.3	–
Kjeldahl-N	27.7	–
Total Nitrogen	28.0	20.9
Total Phosphorus	13.4	12.4
Sodium	64	50.7
Potassium	8.2	9.8
Calcium	12	13.8
Conductivity, µhos/cm	–	424
pH Range	6.3-7.0	

The levels of primary nutrients (N, P, and K) in the sewage effluent reported above are quite high, in some instances exceeding 10 mg/liter; such concentration are high enough to satisfy much or all of the nutrient requirements of high-yielding energy crops. However, if the sewage effluent is diluted with large amounts of nutrient-free water as appears to be the case for the irrigation water being withdrawn from Wahiawa Reservoir (Table 2-1 suggests that the sewage effluent is diluted more than ten-fold before withdrawn for irrigation), levels of nutrient applied to the field would be on the order of 10 pounds per acre-year, much less than the ~200 pounds per acre-year needed by most energy crops. In keeping with WSCo's present practice of ignoring sewage-effluent-nutrients in determining fertilizer application rates, the sewage effluent is ignored in assessing the fertilizer requirements for the energy crop of this investigation.

WSCo has indicated that it plans to continue using the water presently used to irrigate sugarcane after it ceases its sugar operations, employing the present water distribution system. At this writing, WSCo is in the process of creating a private irrigation water distribution company; however, the distribution and rates for water have yet to be established.

3. Selection and Projected Yield of Energy Crop

3.1. Energy Crop Selection

The species of energy crop selected for conversion into electricity depends on its suitability to local conditions, yield, cost of production and delivery, and the specific biomass-to-electricity conversion technology employed. Sugarcane grown commercially in Hawaii is one of the best crops in producing biomass dry matter, and has significant advantages over most other energy-crop candidates, including well developed infrastructure, and cultivation and harvesting practices. Moreover, it is likely that if sugarcane cultivars and agronomic practices were adopted to maximize biomass yield rather than sugar yield, significantly higher biomass productivities could be obtained (Osgood and Dudley, 1993). However, much (one-third or more) of the dry matter contained in sugarcane is in soluble form which is more difficult to harness for conversion into electricity. Several alternative high-fiber-yielding tree and grass species have been found to be better suited than sugarcane for electricity production. Even though some of these alternative crops have fiber yield potentials that exceed that of sugarcane, it is important to note that experience in growing and harvesting most of these crops generally is lacking in Hawaii.

One of the critical factors impacting the economic viability of biomass-for-energy is the yield potential of a crop species under optimal cultural practices. Numerous biomass experiments have been performed in Hawaii which have identified several promising high-yielding species of trees and grasses. *Eucalyptus* and *Leucaena* offer the best commercial potential of the tree species. Trials conducted in Hawaii (e.g., Whitesell et al., 1992; Phillips et al., 1993) have suggested likely commercial yields of ~10 tons/acre-year (unless stated otherwise, all biomass yield and production data in this report are given on a dry-matter basis) from tree crops grown on a multiple-year rotation. Numerous studies have shown that grass species, such as Napiergrass (*Pennisetum purpureum*), have much greater yield potential than the tree species and, under conditions similar to those of this investigation, have an economic advantage; therefore, only grasses are considered here.

The grass yields used in this investigation were projected from a series of experiments conducted by HSPA throughout the State (Wu and Tew, 1989; Osgood and Dudley, 1993) and in a ten-acre energy-grass demonstration on Molokai presently being performed by HSPA and HNEI.

At Hoolehua, Molokai, seven crops — one plant (seeded) crop and six ratoon (regrowth) crops — of banagrass, a variety of Napiergrass, were harvested from a test plot over a 4.3 year period spanning 1987 to 1991. (Note, after the first seven crops, that test plot was left unattended for one year before being mowed and ratooned twice more, yielding eight ratoons from a single plant crop.) Yield results for the first seven crops are presented in Table 3-1. The average dry-matter yield over seven crops was 19.5 tons per acre-year. The data in the table show that crops grown during the summer have much higher yields than crops grown during the winter.

In another series of banagrass yield trials performed by HSPA, involving five locations on four islands in Hawaii, ratoon crops achieved yields that were more than double those of plant crops (Table 3-2). Fiber content in the ratoons averaged 29.6%, whereas plant crops contained only 18.9% fiber. The average yield for plant crops was 18.5 tons/acre-year; by contrast, ratoon crops averaged 42.1 tons/acre-year.

Table 3-1. Banagrass yields (dry matter) in 0.7 acre test plot at Hoolehua, Molokai (HSPA data).

Harvest Number	Harvest Date	Crop Days	Yield[a] (tons/acre)	Dry matter[a] (tons/acre-year)	Season
1	4/20/87	217	6.87	11.55	Winter
2	11/8/87	212	15.80	27.21	Summer
3	5/24/88	188	9.69	18.81	Winter
4	2/22/89	289	15.83	20.35	Winter
5	8/23/89	176	15.10	31.32	Summer
6	4/3/90	223	8.87	14.51	Winter
7	1/8/91	280	11.61	15.13	Winter

a Plots of 40 feet x 40 feet were hand harvested. Three replications were harvested at each date from a 0.7 acre planting.

Table 3-2. Dry matter yields of plant versus ratoon crops for banagrass at five locations in Hawaii (HSPA data).

Location	Yield (tons/acre)		Yield(tons/acre-year)	
	Plant	Ratoon	Plant	Ratoon
Mauna Kea Agribusiness Co.	12.91	36.14	18.84	47.52
HC&S Co.	10.09	31.61	17.04	41.64
McBryde Sugar Co.	8.39	29.62	15.24	32.04
The Lihue Plantation Co.	9.56	39.35	17.40	42.48
Waialua Sugar Co.	12.05	35.32	24.12	47.04

The most notable banagrass trial performed in Hawaii to date is a ten-acre demonstration on Molokai presently underway, managed by HNEI and HSPA, with funding from the National Renewable Energy Laboratory via HNEI's Biofuels Program (Fig. 3-1). (Note, the "ten-acre" banagrass demonstration mentioned throughout this report is termed as such because of the originally planned size of the project; in reality, the size of that project exceeds eleven acres.) In that demonstration, banagrass yields, averaging 16.7 tons/acre, were obtained in the 7.7-month-old plant crop (Table 3-3), giving an annualized yield of 26.1 tons/acre-year. This demonstration, which was harvested in entirety in February 1995 using commercial sugarcane harvesting equipment (including a sugarcane chopper harvester from WSCo), serves as the basis for most of the banagrass yield and economic projections of this investigation. The ratoon crop, under cultivation at the time of this writing (Fig. 3-1; lower figure), appears to be extremely vigorous and likely will outyield (in tons/acre-year) the plant crop significantly.

Fig. 3-1. Ten-acre banagrass demonstration at USDA Plant Materials Center, Hoolehua, Molokai: (upper) plant (i.e., seeded) crop at 7.7 months age; (lower) first ratoon, 2.4 months after harvest of plant crop.

Table 3-3. Results of plot harvests from ten-acre banagrass demonstration on Molokai (unpublished HNEI/HSPA data).

Block	Plot	Moisture content %	Yield-fresh weight[a] tons/acre	Yield-fresh weight[a] tons/acre-year	Yield-dry matter[a] tons/acre	Yield-dry matter[a] tons/acre-year
1	1	76.8	47.2	73.9	10.9	17.1
	2	71.8	64.4	100.8	18.2	28.5
	3	75.0	60.9	95.4	15.2	23.8
2	1	75.7	66.5	104.2	16.2	25.4
	2	75.5	41.8	65.5	10.2	16.0
	3	74.2	50.5	79.2	13.1	20.4
3	1	69.0	72.9	114.1	22.6	35.4
	2	66.4	51.5	80.7	17.3	27.1
	3	72.4	43.0	67.4	11.9	18.6
4	1	66.8	73.1	114.5	24.3	38.0
	2	69.7	64.9	101.7	19.7	30.8
	3	66.0	60.5	94.9	20.6	32.2
Overall	12 plots	71.6	58.1	91.0	16.7	26.1

a Crop planted on 4/12/94 and harvested on 12/1/94 (plots, 20 feet x 2 cane lines spaced 5 feet apart, were hand harvested); age at harvest = 7.7 months (233 days).

The series of trials described above indicate that: (1) with sound management, banagrass yields exceeding 20 tons/acre-year can be achieved on a sustained basis; (2) banagrass ratoon crops normally attain higher yields than plant crops; (3) many ratoon crops can be obtained from a single plant crop without undergoing substantial decline in yield.

3.2. Energy Crop Yields Commercially Achievable

Since the available data on yield versus agronomic conditions (water, nutrients, ...) are not precise enough to predict field-by-field yield differences at WSCo, no attempt was made in this investigation to predict energy crop yields on a field-by-field basis. Instead, only average banagrass yields for all irrigated fields at WSCo and average yields for all unirrigated fields are projected.

Calculations performed previously (Kinoshita, 1984) suggest that sugarcane grown commercially in Hawaii during the late 1970s and early 1980s produced an average dry-matter yield (prior to burning the crop in the field in preparation for harvesting and processing) of 17.5 tons/acre-year, comprising ~60% fiber and 40% sugar. (The yield of unburned sugarcane should not be confused with the commercial dry-matter yield, fiber and sugars, presently being reported by the Hawaiian sugar industry — the latter, the commercial yield, is determined after losses due to field burning and wet cane cleaning are incurred.) The commercial yield of banagrass assumed in this investigation is based on the aforementioned trials performed by HSPA and HNEI and on the commercial yield of sugarcane in Hawaii. In consideration of the available information, it appears feasible to achieve commercial yields of 18 to 25 tons/acre-year (dry basis) of banagrass if inputs (water and nutrients) are not limiting. (Management will play a major role in the actual yields in any biomass-for-energy operation.) The commercial banagrass yields for WSCo assumed in the present investigation are, for irrigated fields (10,400 acres), 22 tons/acre-year; for unirrigated fields (1,600 acres), 18 tons/acre-year. On that basis, the average banagrass yield for all 12,000 acres at WSCo would be 21.47 tons/acre-year.

The banagrass yields reported above, high as they might seem, were achieved with little optimization (breeding and selection, and development of appropriate crop-control strategies). It is likely that if an aggressive breeding and selection program were pursued, higher commercial yields for banagrass than those assumed in this investigation could be achieved. Inherent to the above yield projections is the assumption that inputs are not limiting. If the producer of the energy crop is unable to receive a sufficient return for the biomass feedstock, it is very doubtful that the producer would opt to provide those agronomic inputs needed to achieve the high yields projected above.

4. Biomass Production Strategy and Cost Analysis

Unit operations for banagrass production evaluated in this study include soil preparation, seed production, planting, fertilization, weed control, irrigation, harvesting, transporting, and other field functions. The operational sequences are described in the section immediately below; cost projections are discussed in the following section.

The anticipated organizational structure for field operations, and the number of workers in the various operations for banagrass grown on 12,000 acres of land at WSCo are presented in Fig. 4-1. The process and cost analyses of this chapter terminate at the conversion plant gate; storage, additional feedstock processing, and biomass conversion are discussed in the next chapter.

4.1. Unit Operations

4.1.1. Soil Preparation

At WSCo, sugarcane fields normally need to be plowed and replanted after every harvest (i.e., the fields normally are not ratooned), owing to severe damage to the field caused by push-rake harvesting and in-field hauling by truck-trailer units that contain up to 50 tons of cane and extraneous material. Because of excessive compaction, in-field cane-haul roads require special treatment — large subsoilers, mounted behind track-type tractors, rip in-field roads to a depth of 22 inches. Because different harvesting and transporting equipment would be employed for banagrass, soil preparation would differ from that used for sugarcane in types and sequencing of operations as well as in frequency of tillage. Mechanical harvesters, which cause less damage to fields than do push rakes, and lighter haulers than are presently being used for sugarcane would be employed for banagrass; therefore, ripping of in-field roads would not be needed, nor would the fields have to be prepared after each harvest (it is assumed that five ratoon crops would be obtained from each planting, and that ratoon crops would need essentially no soil preparation).

Soil preparation for plant crops would be similar to that practiced by WSCo for sugarcane plant crops: leveling, as necessary; cross-ripping (using a D-8 or equivalent tractor with 30-inch long shanks) and dragging; multiple passes with large (42-inch) disc harrows; followed by rip-dragging the entire field. This practice should leave the soil prepared to a depth of 18 to 22 inches. Ratoon fields would need little or no preparation.

For the purposes of this study, soil preparation practices for banagrass in fields to be seeded ("plant" fields) are assumed to be similar to those used for sugarcane in WSCo's irrigated fields. The direct labor requirement (ripper and disc-harrow operators) would be three operator-hours or more per acre prepared. Additional labor would be needed for leveling and related operations, bringing the total labor input to about four hours per acre prepared (WSCo's present preparation crew comprises 12 workers who prepare 5000 to 6000 acres per year). Additional cost factors for soil preparation include fuel and other equipment charges (e.g., maintenance, which represents roughly one-fourth of the total cost of this operation), and indirect costs (e.g.,

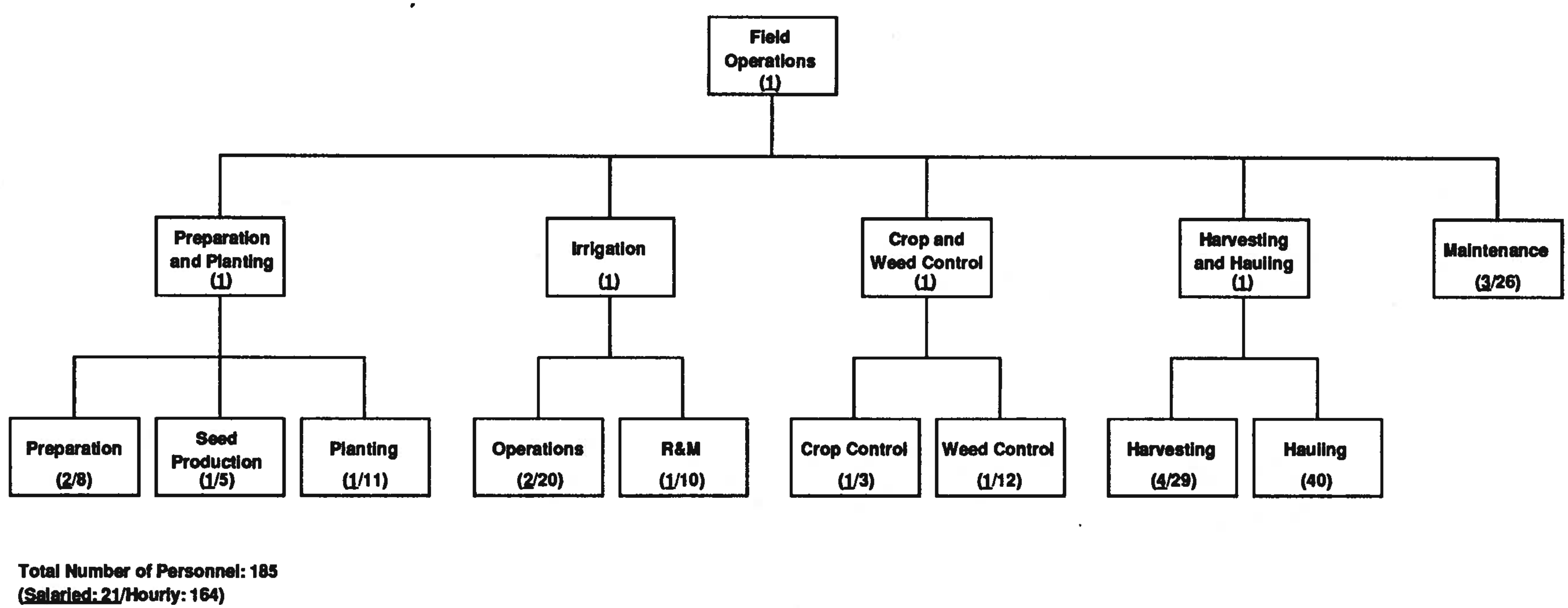

Fig. 4-1. Potential organizational structure for banagrass field operations at WSCo.

insurance and depreciation). These are included in the cost summaries discussed in detail in Section 4.2.

It is assumed that the soil is tilled only prior to planting, and that the soil would not be tilled for ratoon crops; therefore, soil-preparation costs largely would be incurred only in plant crops while ratoon crops would not incur soil preparation costs (although, if deemed necessary, some subsoiling and reshaping of banagrass lines could be performed in the later ratoons as tillering progresses; however, the labor and machine requirements for such operations are very small compared with plant crops; e.g., labor requirements for ratooned sugarcane fields, excluding preparation of in-field cane-haul roads, typically are one order of magnitude lower than those for plant fields).

4.1.2. Seed Production

As mentioned in the preceding section, it is assumed in this investigation that each plant (seeded) crop would be followed with five ratoon crops before the field is plowed and seeded again (note that experience on Molokai suggests that it might be possible to obtain ten or more ratoon crops from each plant crop without suffering significant decline in yield). Because the banagrass would be harvested using mechanical harvesters intended for cutting erect cane which usually produces highly viable ratoon stands needing little or no replanting of voids, and because only one in six crops would be planted, the amount of seed needed per acre cultivated would be much less than that for sugarcane.

The material used to propagate banagrass at WSCo would not be true seed; rather, the crop would be vegetatively propagated using cuttings of the plant stalk (seed pieces). Although selected areas could be set aside specifically for seedcane production, having different row-spacings and inputs, this probably would not be necessary given the rather modest seed requirement. The seed pieces would be ~12–15 inches long, cut from seven- or eight-month old banagrass using the same equipment employed in harvesting the commercial crop (the seed pieces would be planted as is, not stripped of excess foliage). However, care should be exercised so that minimal damage is inflicted to the seed pieces during cutting to ensure high survival and germination rates, and to minimize the need for replanting.

As experienced in the ten-acre demonstration on Molokai, owing to its less-recumbant, more-erect nature, banagrass is easier to cut mechanically than seedcane (i.e., than eight-month old sugarcane used for propagating sugarcane). The similarity in equipment used for harvesting banagrass seed versus banagrass crop enables integration of both operations (by contrast, in Hawaii, the equipment used for harvesting sugarcane seed is dramatically different from that used in harvesting the sugarcane crop) thereby yielding substantial savings in equipment operation and maintenance, and in transporting seed to the plant field. As done for sugarcane seed at WSCo, treating of banagrass seed pieces with a fungicide might be beneficial. However, little information is available on the effect of treating banagrass seed (none of the trials described in Section 3.1 included fungicide treatment); therefore, the value of such treatment is unknown.

In keeping with the more than 50% reduction in application rate (tons of seed applied per acre) of banagrass seed compared with sugarcane seed, the cost of producing and delivering seed to the field to be planted is assumed to be one-half that for sugarcane seed on a per-acre planted basis (refer to Section 4.2).

4.1.3. Planting

Because banagrass stalks have only about one half the diameter of sugarcane stalks, the amount (mass) of banagrass seed applied per acre would be only about one-fourth that for sugarcane (assuming the same degree of overlap of seed pieces placed in the seed furrow). The banagrass seed pieces would be planted in furrows at a depth of <4 inches, and a density of 1.0 to 1.5 tons per acre, using mechanical planters similar to those used for sugarcane in Australia or in Hawaii. That seeding density, while significantly lower than the rate applied for sugarcane (typically ~3 tons per acre), still represents a substantial supply above that used in the ten-acre banagrass demonstration on Molokai (only about 0.7 ton of seed was planted per acre in that demonstration); however, it is believed that generous amounts of seed should be planted because banagrass plant-crop stands tend to be weak. Typical productivities of mechanical planters being used in Hawaii are ~1 acre per hour. The planters are manned by an operator, and several workers on the machine who help to meter seed and on the ground to redistribute seed pieces, and a loader operator to deliver seed to the planter; combined, the labor requirement (not including that for producing seed) is less than 10 worker-hours per acre planted. Drip irrigation tubing and fertilizer (N, P, and K) are injected at the time of planting.

Even though the amount of seed applied per acre would be lower for banagrass than for sugarcane (e.g., 1.0–1.5 tons per acre for banagrass versus 3–4 tons per acre for sugarcane), the cost of planting banagrass (per acre planted basis) is assumed to be the same as for sugarcane. This probably overstates the cost of planting banagrass — although the ground speed of the banagrass planter likely would not differ significantly from that for sugarcane, because the seed application rate would be substantially lower, the percentage of time lost to restocking planting machines should drop markedly, thereby increasing the overall productivity (acres per hour) of the planting operation and reducing cost.

Averaged over several crops, the frequency of planting would be much lower for banagrass than for sugarcane owing to the large number of ratoons expected from each plant crop; thus, the cost of producing and planting banagrass seed would be commensurately lower.

4.1.4. Fertilization

Fertilizer requirements for banagrass are very high — to produce near-maximum yields, >200 pounds per acre of N, >200 pounds per acre of K, and significant levels (50–250 pounds) of P probably would be needed annually. These would be applied initially with the planter as solid fertilizers, and monthly, thereafter, through the drip irrigation tubing in soluble formulations containing N and K.

Because the fertilizers would be applied mostly via the irrigation system, labor requirements would be minimal and the overall cost for fertilization would consist largely of the cost of the fertilizer material itself (e.g., for sugarcane produced at WSCo, materials represent

>80% of the total cost of fertilization; see tabulated cost data in Section 4.2). In this study, the non-materials cost for fertilization was assumed be the same as for sugarcane. The fertilizer (material) requirement for banagrass was assumed to be 35% higher than for sugarcane. Although under some situations, sewage effluent present in the irrigation water at WSCo could provide some of the nutrients needed for banagrass production (refer to Section 2.2.4), in keeping with WSCo's present practice of not including sewage-effluent nutrients in determining fertilizer application rates, the sewage effluent is ignored in assessing the fertilizer requirements for banagrass.

4.1.5. Weed Control

Good weed control is important for ensuring optimal biomass productivity. The most critical stage for weed control is during the first two months after planting, when the crop has the greatest competition from weeds. Good tillage aids weed control by creating a friable, aerated medium for energy-crop roots, eliminating existing weeds, and burying weed seeds. Considerably less weed control would be required for ratoon crops owing to rapid canopy closure following harvest and ground cover from harvesting operations. It is essential to have uniform stands of plant or ratooned banagrass to ensure a high-stalk population for rapid canopy closure and high yield; high seeding density and rapid tillering minimize weed problems. A healthy crop can compete favorably with most annual weeds and is less susceptible to herbicide damage; therefore, water and fertilizers should be applied on a timely basis. Drip irrigation reduces the number of weeds by moistening only the crop rows and keeping the interrows dry and largely free of weeds.

The installation by HSPA of several banagrass trials in Hawaii has led to the development of a weed control program which is expected to be effective at WSCo. Weed control for banagrass cultivation would need to differ from that used for sugarcane owing to the sensitivity of banagrass to a common sugarcane herbicide, ametryn (experience has shown that banagrass is stunted severely by ametryn if the spray contacts the foliage).

The principal weeds at Waialua in sugarcane culture are guineagrass (*Panicum maximum*), swollen fingergrass (*Chloris inflata*), and Aiea morningglory (*Ipomoea triloba*). Many other species are present but usually can be kept under control with an effective weed control program. Banagrass is expected to be infested with the same weeds as sugarcane owing to similar growth patterns of both crops during the first six months.

Guineagrass should be controlled prior to planting by spraying the stools with Roundup (2% by volume in water). Ammonium sulfate should be added to increase Roundup activity.

Weed control in the plant crop would consist of applications of pre-emergence and post-emergence herbicides. In pre-emergence weed control, a combination of atrazine (at 2.5 pounds per acre) and either (at 2.5 pounds per acre) alachlor, trifluralin, or pendamethalin (Prowl) should be applied. Application should be made by a tractor-mounted boom at about 50 gallons per acre within ten days of planting. Post-emergence weed control would consist of carefully spot-treating guineagrass and other grass weeds with Roundup. Broadleaf weeds should be treated with 2.4-D or atrazine.

Few weeds are expected in ratoon crops owing to the rapid growth of banagrass and the anticipated trash blanket on the ground remaining from the previous harvest. Preemergence application, if needed, should follow the practice outlined above for plant crops. Spot treatments should be applied, as needed, using Roundup and 2.4-D.

Canopy closure should occur within eight weeks after planting (slightly longer during the winter), after which in-field weed control would not be needed. Vines such as Aiea morningglory could pose a problem if not controlled prior to canopy closure and along the edge of the field.

Waialua Sugar Company was instrumental in introducing a mechanical spot-application system, called the Spider, to the Hawaiian sugar industry. That system, which has largely eliminated the need for hand application of herbicides, has reduced weed control costs at WSCo significantly (e.g., labor costs for weed control in 1994 were >20% lower than in the previous five years). The same application system should play an important role in any effective weed control program for banagrass.

In this analysis, it is assumed that in the initial planting, the cost of weed control for banagrass is comparable to sugarcane on a per-acre-planted basis (the lower, 1994, cost was assumed). Because banagrass ratoon crops close-in very rapidly, they should need very little weed control (this was the case in the ten-acre banagrass demonstration on Molokai). In this analysis, the cost of controlling weeds in banagrass ratoon fields was assumed to be only one-half the cost of spot application of herbicides in sugarcane fields (in 1994 at WSCo, this represented only ~20% of the total direct cost for weed control).

4.1.6. Irrigation

Commercially grown banagrass would be drip irrigated in a manner similar to that practiced with Hawaiian sugarcane (Bui and Kinoshita, 1985). This involves a network of plastic tubing (laterals) with emitters that "trickle" or "drip" water to the plant in a manner that maintains soil moisture in the plant root zone as close to field capacity as possible during peak-use periods. This method of application is much more efficient in labor, water, and energy use than sprinkler or furrow irrigation.

The drip irrigation system consists of a supply line, which conveys water from the water source to a water treatment station (generally a bank of filter units and a chlorination system) and then to the mainlines that are usually buried to a depth of about 5 feet and maintained at 20–65 psi. A mainline typically serves hundreds of acres and is connected to a series of submain lines, which, in turn, serve as manifolds for the lateral drip irrigation tubes in 1 to 2 acre blocks. The only portion of the system that is replaced on a regular basis is the drip irrigation tubing; however, if the water used in the drip irrigation tubing is of sufficient quality and the tubing is buried slightly, ~8–12 inches deep, it is very likely that the tubing could be left in the ground to be reused in ratoon crops and would have to be replaced only when a new crop is planted (every four years in this analysis). The tubing (and banagrass lines) could be spaced under different arrangements. For example, the banagrass rows could be spaced five feet apart (as in the ten-acre Molokai banagrass demonstration), with drip tubes placed 10–12 inches from each cane line; in this case, 8700 feet of tubing would be required per acre. Alternatively, the banagrass could be spaced in a staggered fashion, e.g., alternating spacings of three feet, then six feet, then three feet, then six feet, ..., with one tube in the middle of the three-foot-spaced pair of cane rows (as being practiced at WSCo); this arrangement would require only 4800 feet of tubing per acre and would provide significant cost savings for drip tubing. It is assumed that the latter, staggered, arrangement would be used for banagrass grown at WSCo (experience in harvesting sugarcane seed suggests that this type of planting arrangement should not present a problem for harvesting).

During the peak-use period, water would be applied at the designed delivery rate of 15 gallons per minute per acre, 12 hours per day. This design criterion is based on the assumptions that evapotranspiration of banagrass near maturity is approximately equal to pan evaporation and that water application efficiency under drip irrigation is ~80 percent. The system would be automated to control water deliveries in the appropriate amounts and timing throughout the plant growth cycle, optimizing the use of water for plant growth. Drip irrigation also can facilitate precise control over the application of nitrogen and potassium fertilizers through their direct injection into the system.

Although more sophisticated to operate, drip irrigation requires less labor than furrow systems and is easier to operate with proper training. Irrigators perform all necessary work to apply water except major repairs. They turn the system on and off, regulate supply water flows, backwash filters (manually or by checking automated equipment), check tube flushing, patrol the fields to ensure proper functioning of the system, and repair minor breaks and malfunctions. Pump failures and supply line breaks require major repairs, which are left to maintenance personnel. Typically, one irrigator can operate and maintain about 350 acres of irrigated crop land, and in some instances as much as 1000 acres; using input from WSCo personnel, this analysis assumes that 20 operators would handle WSCo's 10,400 irrigated acres (see Fig. 4-1), translating to 520 acres per operator. Additional personnel needed to support the drip irrigation system include the maintenance crew, consisting of one worker per 2,000 acres, to repair major equipment (mainlines, submains, risers, filtration systems, etc.), and a tubing installation crew, with a productivity exceeding eight acres per worker-day, to connect tubing to the submains whenever the tubing is replaced. Because of uncertainties associated with the frequency with which the tubing would need to the replaced and the extent of damage to the irrigation system likely to be caused by the banagrass harvesting equipment, the size of the support crew is projected to be ten workers. If the amount of damage to the irrigation system is modest, it is likely that the size of the crew could be reduced to five or six workers.

Because drip irrigation calls for flat culture, mechanization of planting and harvesting is simplified, which has a favorable impact on the economics of ratooning. The cost of weed control is reduced through the removal of waterborne seeds in the filtration process and significant reductions in surface and wetting areas. Flat culture with drip irrigation exposes about 40% less surface area and 200% less wetted area than furrow culture. Also, overflows of excess tailwater with furrow irrigation is eliminated.

The labor requirements for operation and maintenance of the irrigation system should be very comparable to those for drip irrigated sugarcane. However, since the tubing (costing ~$125 per acre, for materials and labor, per installation) would be replaced only once every four years or so instead of once every two years, installation and materials costs would be about one-half that for sugarcane. WSCo personnel are uncertain whether irrigation tubing that is injected to those depths necessary to avoid damage by in-field operations would provide the extent of water movement needed for good germination of seed pieces (as occasionally practiced with sugarcane, adding a surfactant into the irrigation water during the initial application might facilitate lateral and upward migration of water). Alternatively, if deemed necessary, thin-walled drip tubing (which costs less than standard tubing, but which has shorter service life) could be installed at or near the surface to facilitate germination and to irrigate the plant crop; thicker-walled tubing could be injected at greater depths immediately after harvesting the plant crop to serve all subsequent ratoon crops. Indeed, the issues of tubing life (especially in light of potential damage from harvesting and other field operations) and depth of placement need to be resolved before substantial acreages of banagrass are planted.

In this analysis, the cost of the tubing is included with preparation and planting costs (this is consistent with the cost-accounting system for WSCo and facilitates tracking of costs in this analysis for banagrass because the tubing is installed by the mechanical planting units).

At this writing, WSCo is in the process of creating a private irrigation water supply company. Because the rates for water have yet to be established, and because presently water is available is sufficient quantities at WSCo, the cost for supplying water to the field is assumed to be the same as that being charged internally by WSCo at the time of this writing.

4.1.7. Harvesting and Transporting

The banagrass would be harvested, nominally, at about eight months of age. However, the harvesting schedule would have to be adjusted to avoid flowering (terminal growth of banagrass ceases once flowering occurs), which takes place during the months of January to April in crops exceeding four months of age (because flowering depends on temperature and the length of daylight, the extent of flowering would vary from year to year and throughout the plantation).

In this study, harvesting and transporting are discussed together because the distinction between both operations is not obvious. For example, it is not clear whether in-field hauling of the chopped banagrass to the edge of the field for transfer into highway transporting units logically should be included as part of the harvesting or the transporting operation.

Harvesting and transporting were treated differently from the other field operations because those two operations, combined, generally represent the largest components in the delivered cost of most energy crops (e.g., refer to Cundiff and Harris, 1995, for switchgrass; Hubbard and Kinoshita, 1993, for banagrass and leucaena; and Whitesell et al., 1992, for eucalyptus) and because the extrapolation of those costs from sugarcane to banagrass is not as straight forward as the other operations considered above.

The primary banagrass harvesting and transporting systems considered in this study is based largely on commercial sugarcane equipment similar to those used in some industrialized cane sugar industries, most notably for crop cane in Australia and the mainland U.S., and for seed cane in Hawaii. The harvester would gather and cut standing banagrass into billets approximately 12–15 inches long. Since such harvesters (e.g., the Austoft Model 7000 and the Claas Model

CC 1400 sugarcane chopper harvesters) are often used for harvesting unburned cane, they should be directly applicable to banagrass without significant modifications in equipment or practices. (The only modifications would be the disabling of those components used to separate the leaf fraction from the stalk since maximum recovery of biomass is desired.) The harvested material, having a bulk density of about 8 pounds per cubic foot, then would be transferred into in-field tipper trailers commonly used for transporting sugarcane (e.g., units fabricated by Cameco Industries) that self-unload, using tractor auxiliary hydraulics, at the edge of the field for consolidated highway transporting, or the harvested material could be transferred directly from the harvester into highway haulers. Since the highway haulers inevitably would spend a significant portion of time waiting for tipper trailers to collect, transport, and transload the harvested banagrass into the trucks, the truck drivers could assist in the operation of tipper trailers as equipment availability and scheduling permit (thereby reducing the labor required for in-field transporting and transloading by one-half of normal). Fig. 4-2 shows field equipment employed in harvesting and transporting banagrass in the ten-acre demonstration on Molokai in February 1995; similar equipment would be used in one of the harvesting and transporting scenarios presented here.

It seems likely that single in-field tractors could serve double tipper trailer units, thus reducing labor and equipment requirements, yet maintaining high harvester productivity. In the banagrass harvesting operation envisioned for WSCo, highway-legal double trailers, capable of transporting and unloading chopped banagrass would be used. In the operation being considered, the banagrass is transported to the conversion facility immediately after cutting; therefore, the moisture content of the feedstock delivered to the conversion facility would be essentially the same as that of the crop at the time of cutting (~70%).

The round-trip (field to conversion facility, back to field) time between the field and the conversion facility was examined to estimate hauling costs. Currently, WSCo reports round trip times varying from 20 minutes to 2 hours depending on the distance between the field and the factory. In the present analysis, the average round trip was assumed to be 60 minutes. This average haul time, combined with the charge-out rates for transport equipment covering comparable hauling distances, form the basis for the banagrass transporting cost projections.

An alternative harvesting system, in which a forage harvester replaces the sugarcane chopper harvester with all other equipment remaining the same, also appears to be viable. Such a system was tested recently in Texas for harvesting one-year old sugarcane at the Rio Grande Valley Sugar Growers plantation (Mason, 1994). The productivity and recovery of the forage harvester and the properties of the harvested crop appear to be very suitable for energy cane applications. The forage harvester would produce finer particles than sugarcane chopper harvesters, yielding higher hauling densities (perhaps ~50% greater — 12 pounds per cubic foot as opposed to 8 pounds per cubic foot for the chopper harvester system). Transportation costs should be lower, but harvesting costs might increase because of lower harvester productivity. Additional details of both harvesting systems are presented in worksheets in the Appendix.

It is very likely that an operation covering 12,000 acres at WSCo would call for the harvesting of two fields simultaneously; one field being closer to the conversion facility than the other field. By doing so, average haul distances, and, consequently, hauling manning and equipment, would be kept in balance. A common assumption for both harvesting/transporting

Fig. 4-2. Harvesting and transporting banagrass on Molokai: (upper-left) standing banagrass at harvest; (upper-right) Claas Model CC1400 sugarcane harvester transferring chopped banagrass into Vanguard Model V1248-2 tipper trailer (20 cubic-yard capacity) for infield transporting/transloading; (lower-left) transloading banagrass from tipper trailer into truck/trailers (with capacities varying from 30 to 45 cubic-yards) near field edge for highway transporting; (lower-right) harvester transferring banagrass directly into truck/trailers.

scenarios being considered here is that harvesting and hauling operations would be performed in two shifts, whereas the conversion operation would continue around-the-clock, in three shifts. Therefore, it would be necessary to stockpile enough biomass at the conversion facility for the third shift while harvesting is not taking place. A front-end loader or a stacker similar to those used in Hawaiian sugar industry mill yards, would be used to shuttle the stockpiled biomass around the receiving area and feed the first carrier leading to the conversion process (as mentioned earlier, this operation is not included in computing the cost of feedstock delivered to the biomass conversion plant).

4.1.8. Other Field Operations

In addition to the operations described above, other field operations would be needed to support energy crop production, including road maintenance and soil conservation. Because the equipment being proposed to transport banagrass are lighter in weight, with haul capacities lower than the cane-hauling units at WSCo, road maintenance requirements should be substantially less than presently at WSCo (in this investigation, the cost of road maintenance is assumed to be only one-half that for sugarcane).

Some research and crop logging also should be performed. Certain research functions might be handled by the an independent research organization such as HSPA or by the university's extension service. Some in-house work probably would be performed by a plantation agriculturalist, an assistant, and several field workers (designated as Crop Control in Fig. 4-1). This work might include limited field trials, growth measurements, and crop logging. Nutrient analysis of banagrass samples would be taken to monitor growth and nutrient status. However, because sucrose accumulation, plant moisture, and the like need not be monitored (since maximum growth until harvest largely is the sole objective), the amount of work to be performed by the crop control department should be significantly less than for sugarcane.

4.2. Feedstock Cost Predictions

Costs for the operational sequences discussed in this section were projected largely on the basis of costs for commercial sugarcane operations at WSCo. WSCo's cost accounting system contains nearly 800 elements for field and equipment shop functions which fall into three general classifications: labor, materials, and external services. These 800 elements are consolidated by WSCo into broader cost centers, corresponding to ~30 field and maintenance shop operations (see Table 4-1).

In predicting banagrass production costs, the nearly 800 elements for field and field-equipment servicing costs were reviewed first to determine the most significant elements that comprise each (of the ~30) broad cost center and to identify items that should be deleted or modified to make the sugarcane information more relevant and consistent with that for banagrass (a less extensive review of Administrative costs was performed in conjunction with WSCo's accounting personnel).

Table 4-1. Summary of cost elements comprising WSCo's broad cost centers and relationship to banagrass cost centers.

Original WSCo Cost Center	Account Subcategories				Description of WSCo Cost Center	Replacement Cost Center
	Labor	Matls.	Ext.Svc.	Total		
Field						
Preparation	18	12	1	31	Preparation operation (Note: ~40% of labor cost is for planting)	Soil Preparation
Seed Cane	8	5	1	14	Seed cutting operation	Seed Production
Replant-Preparation	6	2	0	8	Replanting operation (performed by preparation crew)	Planting
Road Maintenance	7	5	1	13	Road (off-field) maintenance operation	Road Maintenance
Road Maintenance Equipment	11	10	1	22	Road (off-field) maintenance equipment R&M	Road Maintenance
Trucks & Trailers	14	12	2	28	Hauling cost for seed (from field edge)	Seed Production
Plow Equipment	10	10	1	21	Preparation equipment R&M	Soil Preparation
Plant Equipment	11	10	1	22	Planting equipment R&M	Planting
Seed Cutting Equipment	13	10	1	24	Seed cutting equipment (to field edge) R&M	Seed Production
Replant-Irrigation	5	2	1	8	Replanting operation (performed by irrigation crew)	Planting
Field Maintenance Equipment	10	9	1	20	Equipment for irrigation system repair; cane pushing	Irrigation
Weed Control	16	11	1	28	Weed control operation	Weed Control
Irrigation	65	41	9	115	Irrigation operation	Irrigation
Irrigation System R&M	19	16	1	36	Irrigation start-up (hook-up, drain valves installation, ...)	Irrigation
Storm Damage	3	2	0	5	Repair of storm damage to irrigation system	Irrigation
Water	7	8	2	17	R&M for electrical equipment for irrigation	Irrigation
Ag Control & Research	31	24	4	59	Crop Control	Crop Control/Research
Nursery	11	9	1	21	Transplant production	Seed Production
Fertilize	12	8	1	21	Fertilization operation	Fertilization
Harvest	14	9	2	25	Harvesting operation	Harvesting
Haul	6	4	4	14	Hauling operation	Hauling
Harvest Tractors	11	10	2	23	Harvesting equipment R&M	Harvesting
Canehaulers	14	11	2	27	Hauling equipment R&M	Hauling
Harvest Cranes	10	10	1	21	Harvesting cranes R&M	Harvesting
Field General	18	16	8	42	Supervision	Other Field
Equipment Shop						
Field Maintenance Shop	11	11	1	23	Operation of Field Maintance Shop (not including charge-outs)	Equipment Shop
Equipment Service Shop	10	10	1	21	Operation of Equipment Service Shop (not including charge-outs)	Equipment Shop
Automotive Shop	11	9	1	21	Operation of Automotive Shop (not including charge-outs)	Equipment Shop
Equipment Repair Shop	13	11	2	26	Operation of Equipment Repair Shop (not including charge-outs)	Equipment Shop
Equipment Shop General	13	13	5	31	Operation of Equipment Shop-General (not including charge-outs)	Equipment Shop
Administration						
Energy					Materials primarily boiler fuel; Ext.Svc. primarily electricity revenue	Other General Costs
Supply					Supplies (<1%)	Other General Costs
Controller Department					Controller Department	Controller Department
Industrial Relations					Ext.Svc. includes workers comp., ...	Industrial Relations
Employee Benefits					Ext.Svc. includes FICA, Soc.Sec., Unempl.	Empl.Ben.&Medical
Medical Plans/FASB 106					Ext.Svc. includes post-retirement benefits, medical, ...	Empl.Ben.&Medical
Adminstration General					Ext.Svc. includes deprec., sug./mol. transp., HSPA	Administration General
Net Misc. Sales Expense					Sales (<1%)	Other General Costs
Net Leased Prop. Expense					Leases (<1%)	Other General Costs

As appropriate, actual sugarcane production costs for WSCo were recast according to cost centers more relevant to this investigation (listed as "replacement cost centers" in Table 4-1) and extrapolated, according to selected unit cost bases, to predict banagrass cultivation costs. In most cases, once the appropriate unit basis for a broad cost center was identified, the total cost (labor, materials, and external services, combined) for that cost center could be adjusted quite easily to reflect an equivalent banagrass production operation (according to the replacement cost centers corresponding to the unit operations described in the preceding section). However, in some instances, because of the unique nature of a specific sugarcane or banagrass operation, labor, materials, or external services expenses had to be adjusted separately from the other expenses for the same cost center. In some cases (e.g., harvesting), the present sugarcane operation at WSCo has little relevance to the equivalent operation for banagrass; in those instances, the costs of individual operations were predicted on the basis of anticipated requirements for labor, materials, maintenance, and other inputs relating to the particular operation. To the extent practicable, all adjustments made in this investigation are described in the footnotes of the tables presented below. WSCo's cost data for 1989–1994 were used in this analysis; although this time frame may seem rather long, WSCo's total cost of production did not vary much over that period, and use of a long time frame helps to moderate year-by-year variations in cost.

Waialua Sugar Company's unit production costs for sugarcane and the corresponding unit bases are summarized (according to labor, materials, and external services) in Table 4-2 for the broad cost centers relevant to banagrass. Costs for employee benefits (FICA, social security, unemployment insurance, post-retirement benefits, medical insurance) contributed by WSCo were redistributed into all of the cost centers shown in Table 4-2 preserving the same general classifications, labor, materials, and external services, specified by WSCo (note, at WSCo, most of the employee benefits costs are classified as external services which explains the apparently high cost for external services and the seemingly low cost for labor); all other administrative costs are listed as G&A costs.

Table 4-2 also presents, in a fashion parallel to that described above for sugarcane, the unit bases and the associated unit costs for plant-crops of banagrass. Except for harvesting and transporting, the unit costs for banagrass were projected from WSCo's unit costs for comparable operations with sugarcane. The harvesting and transporting costs for banagrass were calculated from cost projections provided by HSPA (HSPA's estimates, presented in the Appendix, were modified in accordance to the crop harvest age and yield projected here). Although the sugarcane-harvester based system appears to be slightly more costly than the forage-harvester based system, the former was selected for this investigation since the costs for that system are better documented and since that system has been used for harvesting banagrass in Hawaii. It is very likely that newer and larger sugarcane harvesting systems being investigated by the Hawaiian sugar industry (e.g., the Cameco CHT-2500 chopper harvester) might provide opportunities for significant cost savings in harvesting banagrass.

Table 4-3 compares the unit costs for each cost center of the banagrass plant crop versus the ratoon crop. As mentioned in the preceding section, ratoon-crop costs for soil preparation, seed production, and planting are assumed to be nil; weed control costs for banagrass ratoon fields are assumed to be only one-half the cost for spot application of herbicides in sugarcane plant fields; all other ratoon crop costs are assumed to be the same as the corresponding costs for the banagrass plant crop. Table 4-4 summarizes the predicted costs for the plant crop, ratoon crop,

Table 4-2. Summary of sugarcane and banagrass plant-crop costs, by cost center.

Sugarcane—Plant Crop		Unit Cost ($/unit)			
Cost Center	Unit Basis	Labor[a]	Materials	Services	Total
Soil Preparation/Planting[b]	Acre planted	204	213	134	551
Seed Production	Acre planted	58	59	39	156
Weed Control[c]	Acre planted	69	141	16	225
Irrigation	Acre cultivated	99	42	64	205
Fertilization	Acre cultivated	5	101	16	123
Harvesting	Acre harvested	124	104	59	288
Transporting	Acre harvested	123	186	27	336
Road Maintenance	Acre cultivated	9	7	15	32
Crop Control/Research	% of total field	2.1%	2.4%	7.0%	3.7%
Other Field	% of total field	15.8%	1.7%	3.5%	7.4%
Equipment Shop	% of total field	6.3%	1.4%	0.7%	3.0%
Landholding	Acre cultivated	0	0	0	0
G&A—Field[d]	% of total field	9.0%	1.3%	42.0%	16.5%

Banagrass—Plant Crop		Unit Cost ($/unit)			
Cost Center	Unit Basis	Labor[a]	Materials	Services	Total
Soil Preparation/Planting[b]	Acre planted	204	213	134	551
Seed Production[e]	Acre planted	29	30	19	78
Weed Control[c]	Acre planted	69	141	16	225
Irrigation[f]	Acre cultivated	60	25	38	123
Fertilization[g]	Acre cultivated	5	137	16	158
Harvesting[h]	Acre harvested	44	60	42	146
Transporting[h]	Acre harvested	46	48	24	118
Road Maintenance[i]	Acre cultivated	4	4	8	16
Crop Control/Research[j]	% of total field	1.0%	0.4%	3.5%	1.5%
Other Field	% of total field	15.8%	1.7%	3.5%	7.2%
Equipment Shop	% of total field	6.3%	1.4%	0.7%	2.9%
Landholding	Acre cultivated	0	0	0	0
G&A—Field[d]	% of total field	9.0%	1.3%	42.0%	16.2%

a Labor costs include employee benefits.
b Includes cost of consumable irrigation supplies injected by planter (tubing, connectors, and valves).
c Basis for weed control costs is 1994 cost.
d Includes all Administrative costs, prorated, except employee benefits, power plant costs/revenues, sugar/molasses transportation, and HSPA assessments.
e Assumed to be 50% of sugarcane due to reduced application.
f Cost for Irrigation (all categories) reduced by 40% due to elimination of mill water irrigation and furrow.
g Materials Cost for Fertilization increased by 35%.
h Cost for Harvesting and Transporting banagrass calculated from cost estimates provided by L.A. Jakeway, HSPA (see Appendix), adjusted for crop harvest age and yield projected here.
i Cost for Road Maintenance assumed to be 50% of sugarcane due to use of lighter equipment.
j Materials Cost for ripeners, tassel control (~85%) eliminated; other costs reduced by 50% to reflect reduced scope.

Table 4-3. Extrapolation of plant crop costs to ratoon crop costs, by cost center.

Cost Center	Plant Crop Unit Basis	Unit Cost ($/unit)	Ratoon Crop Unit Basis	Unit Cost ($/unit)
Soil Preparation/Planting	Acre planted	551	Acre ratooned	0
Seed Production	Acre planted	78	Acre ratooned	0
Weed Control	Acre planted	225	Acre ratooned[a]	23
Irrigation	Acre cultivated	123	Acre cultivated	123
Fertilization	Acre cultivated	158	Acre cultivated	158
Harvesting	Acre harvested	146	Acre harvested	146
Transporting	Acre harvested	118	Acre harvested	118
Road Maintenance	Acre cultivated	16	Acre cultivated	16
Crop Control/Research	% of total field	1.5%	% of total field	1.5%
Other Field	% of total field	7.2%	% of total field	7.2%
Equipment Shop	% of total field	2.9%	% of total field	2.9%
Landholding	Acre cultivated	0	Acre cultivated	0
G&A—Field	% of total field	16.2%	% of total field	16.2%

a Weed Control cost in ratoon crop assumed to be 50% of spot application cost in plant crop (which is ~20% of total weed control cost for sugarcane).

Table 4-4. Summary of banagrass production costs per acre-crop harvested, per acre-year, and per ton harvested (dry basis), by cost center.

	$/acre-crop			$/acre-year[b]	$/ton[c]
Cost Center	Plant	Ratoon	Average[a]	Average	Average
Soil Preparation/Planting	551	0	92	138	6.41
Seed Production	78	0	13	20	0.91
Weed Control	225	23	56	85	3.94
Irrigation	82	82	82	123	5.74
Fertilization	105	105	105	158	7.36
Harvesting	146	146	146	219	10.22
Transporting	118	118	118	177	8.26
Road Maintenance	11	11	11	16	0.74
Crop Control/Research	28	10	13	20	0.93
Other Field	132	49	63	94	4.37
Equipment Shop	53	20	25	38	1.76
Landholding	0	0	0	0	0.00
G&A—Field	296	109	140	211	9.81
Subtotal—Field	1827	673	865	1298	60.45

a Number of ratoon crops per plant crop = 5.

b Age at harvest = 8 months.

c Assumed yields: irrigated fields (10,400 acres) = 22 tons/acre-year; unirrigated fields (1,600 acres) = 18 tons/acre-year; hence, average for all fields = 21.47 tons/acre-year.and plant/ratoon-cycle (assuming five ratoon crops per plant crop in each cycle) on a per acre harvested basis, per acre cultivated basis (i.e., per acre of crop land per year), and per ton of biomass delivered basis.

and plant/ratoon-cycle (assuming five ratoon crops per plant crop in each cycle) on a per acre harvested basis, per acre cultivated basis (i.e., per acre of crop land per year), and per ton of biomass delivered basis.

The estimated cost of banagrass billets, FOB plant gate, is ~$60 per ton. This dollar figure includes items that often are overlooked, e.g., support operations such as road maintenance, crop control, miscellaneous field operations, and general and administrative functions, which, combined, represent ~30% of the total cost of the delivered biomass. Conspicuously missing in Tables 4-2 to 4-4 is land rent; WSCo presently does not pay rent for the land that it farms. The cost for land rent varies substantially from plantation to plantation in the sugar industry, from nil to over $100 per acre per year. For costing purposes, a reasonable value for land rent on large (≥5000 acres) tracts might be that assumed by Hubbard and Kinoshita (1993) in a study pertaining to dedicated banagrass-for-energy production on Molokai, $65 per acre per year. Given the banagrass yield projected here, such an assigned cost for land rent would add $3 to each ton of biomass delivered to the conversion facility.

As was the case in the aforementioned investigation of banagrass-for-energy production on Molokai, two of the most costly operations in this investigation are harvesting and transporting. (In the investigation for Molokai, for which irrigation represented the largest single cost center, it was assumed that irrigation water was purchased from an independent water supplier; in the present investigation, the source of water and the delivery system is controlled by the energy-crop producer, WSCo, hence water costs are lower, making irrigation less costly than harvesting and transporting banagrass, although it should be emphasized that, here, the cost for irrigation tubing is included with planting, not irrigation.) Harvesting and transporting, combined, represent 30% of the delivered cost of the feedstock. Within the major cost centers — soil preparation and planting, irrigation, fertilization, harvesting, and transporting — and in G&A, there appear to be sufficient opportunities for cost reduction (particularly in the form of higher worker productivity than assumed in this analysis) so that the cost of cultivating and delivering banagrass to the plant site can be reduced by ~10% (to ≤$55 per ton).

The most practical means of reducing the cost of producing each ton of biomass feedstock probably would be to increase crop yield. As mentioned in Section 3.2, it is likely that if an aggressive banagrass breeding program were pursued, higher yields for banagrass than those assumed in this investigation could be achieved. The cost of producing and delivering feedstock to the conversion facility also is affected by the number of ratoons achievable from a single plant crop. The reason for the dependency of overall cost on the number of ratoon crops per plant crop is that the cost of ratoon crops is less than 40% that of the plant crop, due to the elimination of soil preparation, seed production, and planting, and significantly less weed control. The present analysis assumes that one plant crop produces five ratoon crops (over a four-year recurring cycle, comprising six, eight-month-long crops) before yield reduction requires the planting of a new crop from seed. If the number of ratoon crops per plant crop were increased to eight, over a six-year rotating cycle, the average cost per crop would decrease by >7%, reducing the cost of the feedstock delivered to the conversion plant from $60 to $56 per ton (although the drip irrigation tubing might need to be replaced at least once). While eight crops may seem to be a rather large number of ratoon crops to expect from a single plant crop, it should be noted that a recent harvest of a 0.7 acre banagrass test on Molokai (described in Section 3.1), which has undergone eight ratoons in seven years (and was unattended for part of that period), yielded the equivalent of

23 tons per acre-year of dry matter in the eighth ratoon, significantly higher than the original plant crop yield of 12 tons per acre-year.

The costs displayed in Tables 4-2, 4-3, and 4-4 are structured according to WSCo's internal cost accounting system and on its actual wage schedule wherein the average bargaining-unit employee earns ~$10 per hour (in direct wages, not including benefits). Because wages and employee benefits comprise a major portion of the overall cost of producing banagrass, any significant change in wage rates or benefits, upward or downward from WSCo's present levels, could have a dramatic effect on the ultimate cost of the biomass feedstock.

Finally, because the costs for banagrass were projected largely from WSCo's actual operating costs, the banagrass costs reported here reflect efficiencies and deficiencies inherent in WSCo's present sugarcane operations and management. To the extent that improvements might be achievable in WSCo's sugarcane operation leading to lower costs, comparable cost reductions should be achievable in a banagrass operation at WSCo.

4.3. Labor Requirements

Labor requirements (the largest cost component, including fringe benefits) for field operations, including repair and maintenance of equipment, translate roughly to one worker per 65 acres (~185 workers for 12,000 acres; see Fig. 4-1). The majority of the workers would be involved in irrigation (~30 workers to maintain the irrigation supply infrastructure, install drip tubing, and operate and maintain the drip irrigation system), and harvesting and transporting biomass to the conversion facility (~70 workers, not including equipment support personnel).

5. Conversion of Biomass into Electricity

5.1. Feedstock Processing

Assuming a processing season of 320 days per year, the 12,000 acres at WSCo, yielding nearly 260,000 tons of banagrass fiber per year, would need to deliver, nominally, ~800 tons (dry basis) of banagrass per day. Upon delivery at the conversion facility (assumed to be located at the present WSCo sugar factory), the harvested banagrass in the truck would be weighed on a platform scale, unloaded at the receiving station, stockpiled in an outdoor storage yard, and then transferred to the conversion facility for additional processing before being converted into electricity. Unlike sugarcane, which must be processed shortly (within about twelve hours) after harvesting to prevent significant sugar degradation, the banagrass may be stockpiled at the receiving station much longer without undergoing significant loss, the limiting factor largely being the amount of storage space available. This provides greater flexibility, ultimately leading to lower costs, in scheduling harvesting and transporting of banagrass than sugarcane. There appears to be sufficient space in the WSCo factory complex (e.g., adjacent to the present cane cleaner or by displacing the cane cleaner which no longer would be needed) for outdoor stockpiling of at least 4000 tons (as-received basis) of chopped banagrass, capable of accommodating more than 24 hours of banagrass delivery.

The delivered banagrass probably would be sampled periodically (perhaps three samples from each field harvested except those less than 50 acres in size) at the receiving station to monitor the quality of the material delivered to the processing facility, and routinely (perhaps twice every shift) after dewatering to monitor the quality of the material to be converted into electricity. Moisture and ash content in the feedstock are two important feedstock properties and are easily measurable at the conversion facility; therefore, those two properties would be monitored at the conversion facility; other properties, such as those listed in Tables 5-1 and 5-2 of Section 5.2, would be measured on a less frequent, or as-needed basis, by independent laboratories. It is likely that, as experience is gained in handling and converting banagrass, the extent of process control depicted here (e.g., weighing all trucks at the receiving station and extensive monitoring of the quality of the feedstock from each field) might be found to be unnecessary and some of the monitoring activities could be reduced or eliminated. Since this investigation assumes that harvesting and hauling are not performed at night (even though, if deemed necessary, harvesting and hauling could take place around-the-clock as practiced at most Hawaiian sugarcane plantations) some of the biomass delivered to the conversion facility would need to be stockpiled for processing at night. Front-end loaders or stackers would transfer the stockpiled biomass from the outdoor storage yard to the conversion plant. WSCo personnel project that the cost of that operation, not included in the feedstock costs presented in Table 4-4, would be <$2 per ton.

The extent of feedstock preparation needed prior to conversion into electricity depends on the conversion technology pursued. Two biomass-to-electricity technologies are considered here: (1) medium-pressure (≥800 psi) steam generation systems; and (2) biomass gasifier/gas-turbine combined-cycle systems. The banagrass feedstock delivered to the conversion facility, ~1 inch in diameter and 12–15 inches long, would need to be processed further owing to the large size of the feedstock and its high moisture content (~70%). One efficient and proven means of converting the harvested banagrass into a fuel suitable for firing in a boiler furnace would be mechanical processing, such as that depicted in Fig. 5-1. The stockpiled banagrass, having a density of ~8 pounds/cubic-foot (fresh basis), would be transferred from the storage yard, as needed, to the primary carrier leading to the knifing operation. The knifed banagrass, with a density of ~20 pounds/cubic-foot (fresh basis), then would pass a magnetic separator to remove tramp metal, before entering a crushing or shredding station for further preparation. If deemed advantageous or necessary (see Section 5.2.1), the prepared banagrass could be washed to remove alkalis. The banagrass then would enter a three-, four-, or five-roll mill for dewatering to ~50% moisture content. Following milling, the banagrass would have a consistency resembling that of sugarcane bagasse. Based on WSCo present cost for its cane milling operation ($ per ton fiber processed) and assuming that the milling operation would be reduced substantially for banagrass as described above (presently, a five-mill tandem is installed at WSCo), it is anticipated that dewatering would cost ~$4 per ton (dry basis). The milled banagrass then would be conveyed into covered storage (a bagasse storage/reclaiming unit presently exists at WSCo, having a capacity of several hundred tons, dry basis; however, as described below, a much larger storage system probably would be needed here). For the processing rates being considered here, the total amount of power needed to prepare the banagrass for conversion into electricity, including power for conveyors, and other auxiliary equipment, would be ~2300 hp. A rough breakdown of the power requirements for the major processing units is given in Fig. 5-1. The knife, ~350 hp, probably would be driven by electric motor. The crushing or shredding station, ~700 hp, and the dewatering mill, ~1000 hp, probably would be driven by steam turbine. The latter two steam-driven units could be driven by electric motor instead, if the biomass-to-electricity conversion technology selected deemed such an arrangement to be advantageous.

The present cane processing facility at WSCo is rated at 210 tons of "net cane" per hour (Hawaiian Sugar Planters' Association, 1991); for typical conditions at WSCo, this translates to a milling rate of about 33 tons of fiber per hour. That milling rate is essentially the same as the projected nominal delivery rate for banagrass, although the latter does not allow for processing delays which would require the milling capacity to be ~15% greater. Nevertheless, it appears that the present milling plant should not need to be modified extensively to process the entire banagrass crop (note, as mentioned above, this investigation assumes that the processing season would be 320 days long, i.e., ten-and-one-half months of continuous operation, which is substantially longer than the present processing schedule at WSCo, eight to nine months per year). A less demanding schedule could be obtained by adding a parallel milling system, using one of the remaining mill units at WSCo after the sugar operation ceases in 1996, to double the capacity of the processing facility, and preparing banagrass feedstock in a three shift operation (e.g., five operating days per week, allowing for two days of maintenance, if needed), instead of continuously, in a four-shift operation. In such a schedule, some dewatered banagrass would need to be stored so that fuel would be available for the power generation plant during the maintenance period. This would require the installation of covered storage having a capacity of roughly 2000 tons (dry basis).

If the feedstock were to be used in a biomass gasification/gas turbine system, the milled banagrass would have to be dried further, to ~20% moisture content. The most likely scenario for processing the banagrass delivered to the conversion facility calls for mechanical dewatering (as described above) to ~50% moisture content and then drying the processed banagrass, using waste-heat most likely from flue gas emitted by a waste-heat recovery boiler, from 50% to 20% moisture content. (It should be noted that other economic evaluations of biomass-based electricity or

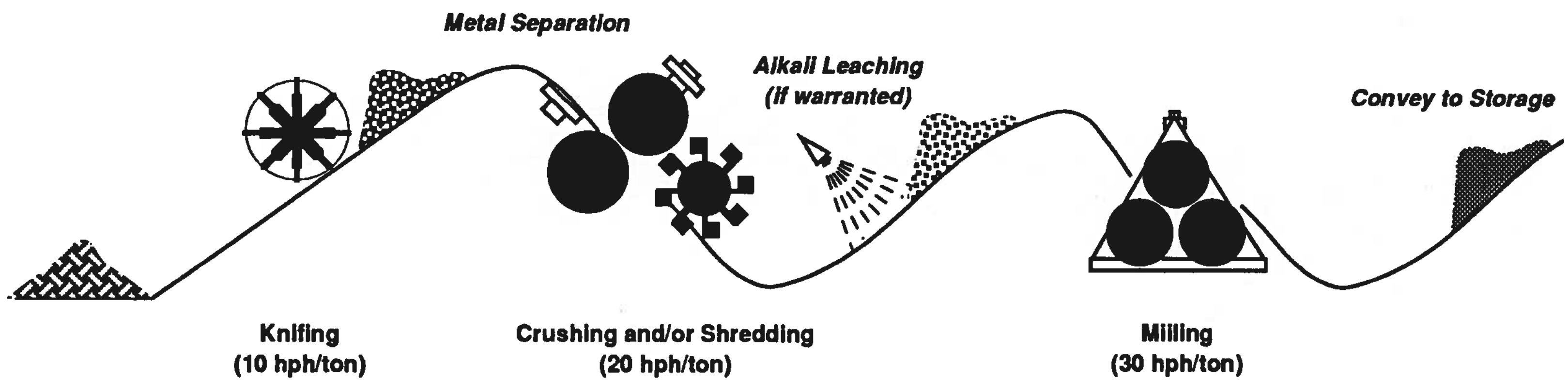

Fig. 5-1. Preparation facility to convert stockpiled banagrass billets into dewatered feedstock for conversion into electricity.

transportation fuel production systems generally assume that the feedstock is supplied to the conversion facility at ~50% moisture content, and include the cost of additional drying with the operation of the facility.)

5.2. Feedstock Characteristics

Properties of the banagrass feedstock are summarized in Table 5-1 (properties for sugarcane bagasse are included as a basis of comparison).

Table 5-1. Comparison of properties of banagrass and sugarcane bagasse (dry basis).

	Banagrass 1995[a]	Banagrass 1990[b]	Average[c]	Sugarcane Bagasse[b]
Proximate Analysis (wt. %)				
Volatile Matter	73.0	77.2	75.1	82.1
Fixed Carbon (by difference)	21.7	17.9	19.8	14.8
Ash	5.3	4.9	5.1	3.1
Total	100.	100.	100.	100.
Ultimate Analysis (wt. %)				
Carbon	45.7	46.6	46.2	47.9
Hydrogen	5.5	5.8	5.6	6.2
Sulfur	<0.1	<0.1	<0.1	<0.1
Nitrogen	0.6	0.7	0.6	0.6
Oxygen (by difference)	42.8	42.0	42.4	42.2
Ash	5.3	4.9	5.1	3.1
Total	100.	100.	100.	100.
Gross Heating Value (Btu/lb)	7800	7900	7800	8200
Ash-Fusion Temperature (°F)[d]		>1900		>2200

a Banagrass sample collected in ten-acre Molokai demonstration (see Table 3-3).
b From Kinoshita and Wang (1990).
c Used in this investigation.
d Based on initial deformation.

Banagrass is similar to bagasse in many respects, except its ash content is slightly higher (although under adverse harvesting conditions, bagasse ash content may increase to very high levels, sometimes approaching 10%), and the ash-fusion temperature is somewhat lower; these characteristics could be problematical in converting the feedstock into electricity.

5.2.1. Ash Deposition

Conventional boilers fired with biomass feedstocks having high levels of alkali and alkaline earth metals are prone to fouling due to the formation of ash deposits. Ash deposition and agglomeration can degrade boiler performance by reducing heat transfer, accelerating metal tube corrosion, and restricting flow through the boiler. The problem of boiler fouling by ash deposits is receiving greater attention, and several studies have been conducted to elucidate the mechanisms of ash deposition in various types of boilers (e.g., Baxter, et al., 1993; Jenkins, et al., 1994). It is known that biomass fuel properties (e.g., the chemical form of inorganics contained in the feedstock), boiler design, and boiler operating conditions are important in determining the mechanisms that control ash deposits.

The primary elements in biomass fuels that are responsible for ash deposition during combustion are believed to be potassium, sodium, silicon, calcium, chlorine, and sulfur. Potassium and sodium volatilize readily into compounds (mainly oxides, hydroxides, and metallo-organics) that actively participate in slag formation. Although silica does not, by itself, form ash deposits, it can react with volatile, or atomically dispersed, potassium species to form problematic low-melting point compounds. Alkali metals have a tendency to form eutectic structures with other mineral compounds under combustion conditions. Eutectic mixtures of potassium oxide (K_2O), sodium oxide (Na_2O), and silica (SiO_2), have lower fusion temperatures than oxides in pure form; e.g., a mixture of 32% K_2O and 68% SiO_2 melts at 1420°F, whereas pure SiO_2 melts at 3090°F (Miles, 1993). Calcium, a relatively refractory element that does not volatilize readily, can be a prominent fly-ash constituent that participates in deposit formation by particle impaction. Chlorine facilitates condensation of potassium chloride salt on surfaces and forms sticky coatings that enhance particle attachment (Jenkins, et al., 1994). Sticky ash particles large enough to coalesce on combustor grates can form a low-melting liquid which solidifies with various particles in the gas stream (e.g., dirt and sand) to produce large agglomerates. Deposits formed by sulfation of alkali compounds occur via gaseous reactions between sulfur oxides and potassium chloride (KCl) or potassium hydroxide (KOH), or via reactions between sulfur oxides and alkali compounds already deposited on boiler surfaces.

Boiler design and operating conditions are important in determining the mechanisms that control ash deposition. The predominant mechanisms for ash deposition have been identified as chemical reaction, thermophoresis, condensation, and particle impaction (Baxter, et al., 1993). The mechanism that forms ash deposits on combustor walls at relatively high temperature (~1650°F) is hypothesized to involve high-temperature chemistry, as the deposition temperature is higher than the estimated dew point for alkali vapors. Alkali vapors, containing mostly potassium, are believed to be vaporized and convected with other volatiles early in the combustion process. The impregnation of dehydrated SiO_2 grains by readily vaporized potassium particles decreases the melting point of the resulting mixture; therefore, the mixture becomes molten, and granular silica originally present in the grains sinter to form glassy, nodule-type deposits on combustor walls. Both molten and sintered phases exist in these high temperature deposits (Baxter, et al., 1993).

Alkali condensation and thermophoresis become dominant mechanisms for ash deposition in cooler regions of the combustor, such as cool reactor surfaces (~680°F), and in regions having large thermal gradients, respectively. Deposits can form when alkali vapors react in the gas phase to form low-melting-point compounds that condense on cool surfaces. Alternatively, deposits can form when vapors initially deposit on cool surfaces and subsequently react with oxide species. Gas composition and local gas temperature are important in that they can affect the hierarchy of alkali compound formation. The presence of chlorine in the gas favors the formation of chlorides; however, the absence of chlorine favors the formation of hydroxides. Oxides are thermodynamically favored when hydroxides are absent, and sulfates are favored at low temperatures.

The mechanism of particle impaction becomes dominant when entrained particles, of the appropriate size, are prevalent in the gas stream. Silicates that do not readily vaporize during combustion remain in the flyash; therefore, these compounds can form deposits as they impact thin slag layers that line boiler tube passes (e.g., alkali vapor condensation, occurring on cool surfaces, providing a layer for deposits). Deposits resulting from particle impaction form on leading edges of tube passes and are dependent on particle size. Particles smaller than 5 µm follow streamlines around the tubes, while larger particles not within the affected size range (which thus far has not been identified for biomass fuels) can rebound off tubes walls (Jenkins, et al., 1994).

Thorough understanding of ash properties for crops being considered for energy conversion, such as banagrass, is important in determining the likelihood of ash deposition in boilers and other power-generation system components. Ash properties for banagrass are summarized in Tables 5-2. Analytical results indicate that the predominant component in the ash is potassium, and that silicon and chlorine are present in sizable quantities. As discussed earlier, these elements participate in ash deposition in boilers.

It has been suggested that an indexing method employed in the coal industry to classify fuels according to slagging potential also might be applicable to biofuels (Miles, 1993). The index, expressed in pounds of alkali (Na_2O plus K_2O) per million Btu (MMBtu), is used to classify fuels as follows: fuels with indices <0.4 lb/MMBtu pose little risk; fuels with indices between 0.4 and 0.8 lb/MMBtu pose moderate risk; and fuels with indices >0.8 lb/MMBtu pose high risk. It appears, based on the above classification, that banagrass, which has an index of ~3.0 lb/MMBtu (using data from Tables 5-1 and 5-2), is likely to cause slagging in boilers. By comparison, sugarcane bagasse (which is leached during the sugar extraction process) and hybrid poplar wood have much lower indices; e.g., sugarcane bagasse has an index of ~0.3 lb/MMBtu (based on data reported by Miles, 1993) to ~0.6 lb/MMBtu (based on data in Tables 5-1 and 5-2), and poplar wood has an index of ~0.5 lb/MMBtu (Miles, 1993).

The potential problem of boiler fouling by ash deposition may require implementation of additional feedstock pretreatment prior to firing. Since some of the major elements involved in ash deposition (e.g., potassium, sodium, and chlorine) are water soluble, leaching processes might be employed to remove a portion of these problematic elements. Comparisons of the potassium and sodium concentrations in bagasse versus molasses ash suggest that the majority of the potassium and sodium in sugarcane are leached out of cane during juice extraction (Kinoshita, 1995), thus reducing the likelihood of ash deposition during the firing of bagasse. Similarly, removal of sufficient quantities of alkali compounds from banagrass via leaching may greatly reduce the likelihood of ash deposition in the combustion of banagrass. Table 5-2 shows that banagrass has 0.02% water soluble Na_2O and 2.4% water soluble K_2O. Additional research is needed to evaluate pretreatment processes and to investigate the behavior of inorganic constituents in banagrass in ash deposition. Information gained from this research may facilitate the judicious use of biomass resources as fuels for conventional boilers.

Table 5-2. Composition of ash in banagrass and in bagasse; water soluble alkalis in banagrass.

	Banagrass[a]	Bagasse[b]
Elemental Analysis, wt. % ash		
SiO_2	27.67	56.1
Al_2O_3	0.36	2.2
TiO_2	0.12	
Fe_2O_3	1.13	6.5
CaO	3.76	5.6
MgO	2.99	4.6
Na_2O	0.73	1.7
K_2O	45.90	13.4
P_2O_5	4.14	
SO_3	1.58	
Cl	13.00	
CO_2	1.77	
Water Soluble Alkalis, wt. % dry biomass		
Na_2O	0.02	
K_2O	2.37	

a Banagrass sample collected in ten-acre Molokai demonstration (see Table 3-3).
b Bagasse data from Paturau (1989) for Hawaiian sugarcane bagasse ash (only those compounds reported are presented).

5.3. Conversion into Electricity

The bagasse cogeneration system currently in place at WSCo is shown in Fig. 5-2. It comprises a relatively low-pressure (460 psi) steam generator with a single automatic-extraction/condensing turbogenerator (with a capacity of 12 MW under extraction/condensing mode, and 9 MW under full-condensing mode). At a bagasse feed rate of 25–30 tons per hour (dry basis), the cogeneration system produces about 10–11 MW (gross generation). Calculations performed in this investigation suggest that if the existing cogeneration facility were retained, with only the turbogenerator and condenser replaced to accommodate reduced extraction (due to elimination of the sugar processing station), the present system would be capable of generating up to 20 MW at a steaming rate of ~300,000 pounds per hour. This projected maximum generation rate for the existing system (modified moderately, as described above) calls for a banagrass fuel

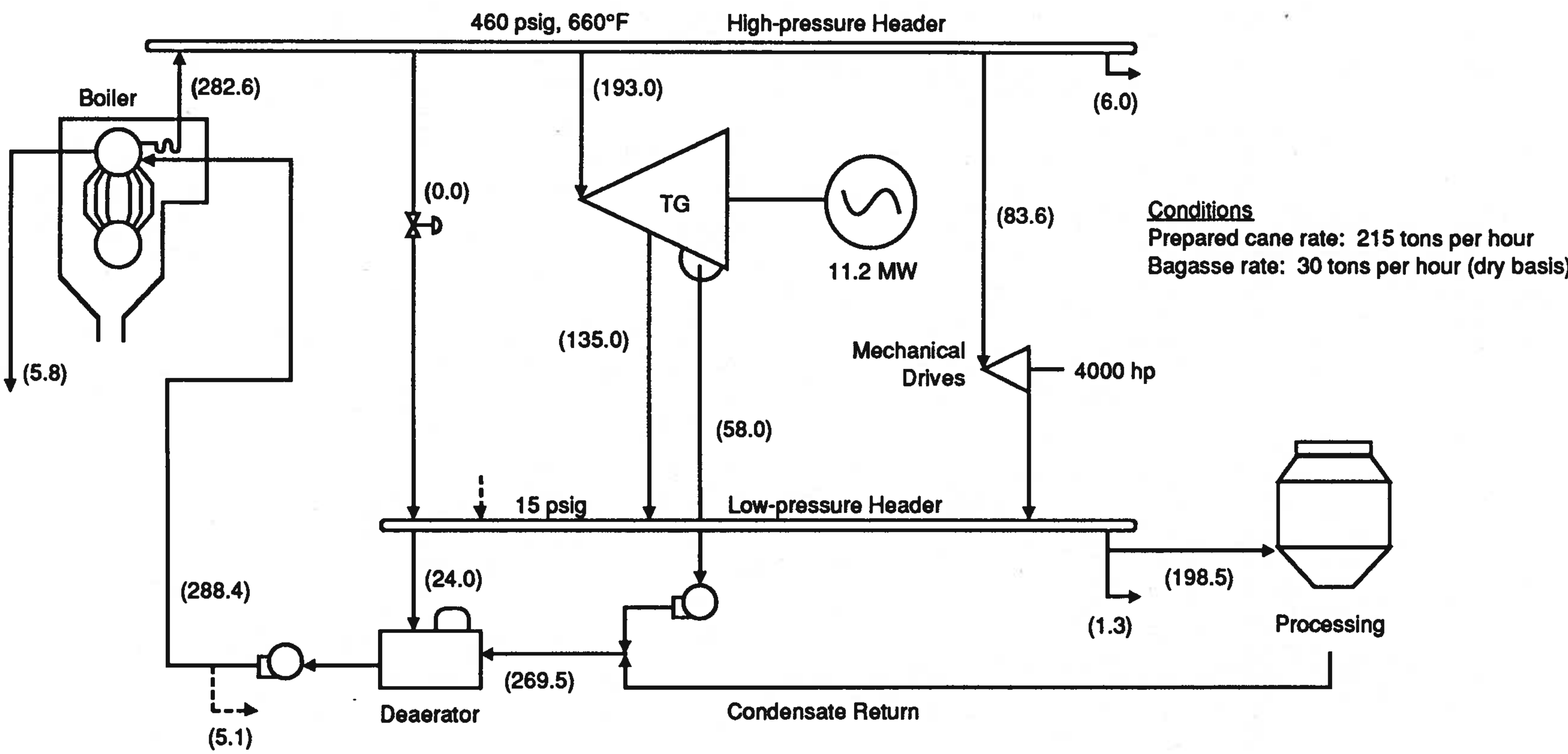

Fig. 5-2. Existing cogeneration facility at WSCo (numbers in parentheses denote steam flows in 1000 pounds per hour).

rate of ~33 tons of fiber per hour, which matches very closely the projected delivery rate of banagrass in this investigation. Because most of the major mechanical units in the present system are driven by steam turbine, nearly all of the 20 MW generated would be exportable. This translates to an overall efficiency — exportable power divided by feedstock gross heating value — of 13% (net heat rate of ~26,000 Btu/kWh).

As mentioned earlier, two biomass-to-electricity technologies are considered as logical replacements for the existing low-pressure steam generation system in place at WSCo: (1) medium-pressure (≥800 psi) steam generation systems; and (2) gas-turbine based combined-cycle systems. The biomass-energy-to-electricity conversion efficiency for the medium-pressure steam generation system is estimated to be 25% (13,700 Btu/kWh heat rate; 1140 kWh/ton overall conversion), while that for the gas-turbine based combined-cycle system is estimated to be 31% (11,000 Btu/kWh heat rate; 1420 kWh/ton overall conversion). The conversion efficiencies for the two biomass-for-electricity options are averages of published and unpublished values (e.g., from Larson and Williams, 1990; Electric Power Research Institute and SFA Pacific, 1993; Craig and Mann, 1993; Bain, 1994). The steam-turbine cycle, based on spreader-stoker boilers or fluidized-bed boilers, represents conventional biomass electricity generation technology. The gas-turbine combined cycle incorporates commercially available aero-derivative or industrial gas turbine technology with existing steam generation technology. However, even though the power generation portions of gas-turbine based systems are commercial, their integration with biomass gasification and clean-up of the biomass-derived gas still are in the developmental stage. Scale-up and demonstration of those technologies presently are underway in Hawaii (Overend, et al., 1992) and elsewhere; technological risk is considered by most in the field to be moderate. Given the higher efficiency of the gas-turbine based system, the moderate developmental risk of such technology, and the relatively short lead time anticipated for commercializing the technology, only the gas-turbine-based option is considered in the following discussion on electricity cost. The following discussion on the cost of generating electricity using gas-turbine combined cycle systems covers only a single estimate pertaining to a specific biomass-to-electricity conversion technology, and was not intended to be a comprehensive comparative analysis of competing conversion processes.

The cost of generating electricity using gas-turbine combined cycle systems was estimated from projections provided by four independent technoeconomic evaluations of biomass gasifier/gas-turbine combined-cycle electricity generation systems. The four separate evaluations are described in a detailed comparative study by Craig and Mann (1993). The same four systems were reevaluated by Bain (1994); the results of the reevaluation, less feedstock cost, are summarized in Table 5-3.

Explanations for the substantial differences in the four estimates of electricity generation cost in Table 5-3 are offered by Craig and Mann (1993). The average values for unit cost and scale ($0.054 per kWh at 56 MW) in Table 5-3 were used as the basis of the present investigation. A comparison of the projected costs for eleven biomass power systems (Craig and Mann, 1993) suggests that unit cost ($/kWh) scales with capacity (MW) roughly according to a 0.7 power. That power factor was applied to the aforementioned base cost and scale ($0.054/kWh at 56 MW) to project electricity costs, less feedstock cost, for electricity generation facilities of different sizes.

Table 5-3. Technical and cost data for four biomass integrated gasification/gas-turbine combined cycle power systems; 1993 costs (Bain, 1994).[a]

	EPRI	Tecogen	Ebasco	NREL	Average
Facility Size (MW)[a]	50	50	64	60	56
Capital Cost ($/kW)[a]	3005	1850	1706	1680	2060
Efficiency (%)	28	29	29	37	31
Electricity Cost (cents/kWh)[a]					
Capital	4.2	2.6	2.3	2.3	2.9
O&M	4.1	2.1	1.7	2.4	2.6
Total (less feedstock)	8.3	4.7	4.0	4.7	5.4

a Net power generation; all figures are rounded.

The total cost of generating electricity from 12,000 acres of banagrass at WSCo, via a gas-turbine based combined-cycle system, is estimated to be $0.101 per kWh, comprised of a feedstock cost of $0.044 per kWh and a conversion cost of $0.057 per kWh (Table 5-4). The cost of biomass feedstock ($3.88 per million Btu) is slightly higher than the cost of petroleum fuels presently being used by the utility company for electricity generation on Oahu (which, over the past five years, has averaged ~$3.40 per million Btu). However, certain economic factors not included in this analysis could help to improve the outlook for biomass energy, e.g., renewable energy production credits and accelerated depreciation for closed-loop biomass energy systems, potential offsets in emissions charges, incentives presently being considered by the federal government, as well as credits for the utilization (disposal) of sewage effluent. For example, presently, federal renewable energy production credits are equivalent to $0.015 per kWh (which translates to $1.10–$1.40 per million Btu in feedstock energy value, depending on the conversion technology employed). Also, WSCo has negotiated or is presently negotiating with the federal and city governments to receive compensation for handling sewage effluent from the Schofield and Wahiawa wastewater treatment plants, respectively; such compensation could help significantly in offsetting the cost of growing the feedstock and converting it into electricity (e.g., $1 million per year in compensation helps to offset the cost of producing feedstock by ~$4 per ton or the cost of generating electricity by $0.003–$0.004 per kWh).

It is possible that other conversion systems might be less costly to install and operate than the advanced gas-turbine based system considered above (e.g., as discussed earlier, the existing cogeneration facility at WSCo might be upgraded at moderate cost by replacing the turbogenerator and condenser, yielding a biomass-to-electricity conversion facility with an overall efficiency of approximately 13%); however, any resultant savings in biomass-to-electricity conversion cost must be weighed against likely increases in the apparent cost of the fuelstock following reduced conversion efficiency. For example, if the overall efficiency were only 13%, the banagrass feedstock (at $60.45 per ton) would represent a very costly fuel component of $0.10 per kWh exported.

Table 5-4. Feedstock cost and electricity generation (numbers are rounded).

Biomass Feedstocks from 12,000 Acre Plantation at WSCo		
Feedstock form at plant gate	billets	
Feedstock moisture content at plant gate (%)	70	
Annual delivery to conversion facility, dry basis (tons/year)	257,600	
Delivery rate, dry basis (tons/day)[a]	805	
Heating value (million Btu/hour)[b]	523	
Feedstock cost ($/ton)[c,d]	60.45	
Feedstock cost ($/million Btu)[b,d]	3.88	
Type of conversion technology	Conventional	Advanced
Conversion plant efficiency (%)	25	31
Heat rate (Btu/kWh)	13,700	11,000
Conversion efficiency (kWh/ton)	1140	1420
Gross generation potential (MW)	38.2	47.6
Exportable electricity (MW)[e]	36.2	45.6
Annual exportable electricity (million kWh/year)	278	350
Feedstock cost (cents/kWh)[d]	5.6	4.4
Conversion cost (cents/kWh)[f]		5.7
Total electricity cost (cents/kWh)		10.1

a Based on 320 operating days per year.
b Based on feedstock heating values in Table 5-1.
c Refer to Table 4-4.
d Additional costs for handling and processing biomass feedstock into fuel might be incurred (refer to discussion in Section 5.4 and Table 5-5).
e Assumes 2.0 MW load for processing biomass feedstock into fuel.
f Scaled (according to 0.7 power) from unit cost of $0.054 per kWh at 56 MW (average of data in Table 5-3).

The rate of electricity producible (net generation for power plant, exclusive of banagrass preparation system) from a conventional power plant is 38 MW, while the rate from the advanced system is 48 MW. Approximately 2 MW of those rates would return to the conversion facility for processing the banagrass billets into banagrass fuel (based on the 2300 hp requirement mentioned in Section 5.1 plus one-third additional to meet losses and miscellaneous loads); the balance — 36 MW for the conventional system and 46 MW for the advanced system — would be available for export to the utility company. These export rates translate to ~280–350 million kWh annually.

As demonstrated above, conversion-plant efficiency can have a major impact on the effective cost ($/kWh) of the feedstock. The "conventional" efficiency of 25% assumed in this investigation should be achievable with existing biomass power generation equipment, considering that the better power generation facilities in the Hawaiian sugar industry already have efficiencies approaching 20% under full-condensing modes. Predictions of power-generation efficiencies of advanced biomass power generation systems (e.g., gas-turbine-based combined cycles or steam-injected gas-turbines) vary from 28% to >35% (Bain, 1993; Larson and Williams, 1990), with the potential to exceed 40% (Williams, 1989). The "advanced" efficiency of 31% assumed in this investigation should be achievable and probably surpassed once scale-up efforts presently underway in Hawaii (Kinoshita and Trenka, 1994) and elsewhere, are completed. Any increases in conversion efficiency over the level assumed in this investigation would yield commensurate reductions in apparent feedstock cost (i.e., $ per kWh attributable to fuel).

It is anticipated that ~25–30 workers, including supervisory personnel, would be needed in the biomass power generation facility (in a continuous operation); approximately 18 employees would be involved in the day-to-day operation and maintenance of the facility (up to ten additional workers might be needed if substantial fuel preparation is necessary), and seven employees would be responsible for repair and maintenance, and support (e.g., welding, electrical, analytical) functions.

5.4. Costs and Savings Not Included Previously

Several potential costs and savings alluded to in this and the preceding chapters are not included in the cost summaries of Tables 4-4 and 5-4. These were omitted primarily because the costs did not apply to WSCo during the base years of this investigation (but might apply to other plantations and to WSCo in the future) or because insufficient information exists to quantify the costs or savings (this pertains especially to biomass processing operations, which are not formally part of the scope of this investigation). Table 5-5 attempts to provide estimates for the likely magnitudes of such costs and savings.

As mentioned previously (Section 4.2), land rent varies substantially throughout the sugar industry, from nil to over $100 per acre per year (presently, WSCo does not pay rent for the land that it farms; therefore, no cost for Landholding is shown in Table 4-4); the amount shown in Table 5-5, $65 per acre per year, represents a typical cost. The costs shown in Table 5-5 for biomass handling and dewatering, $2 and $4 per ton, respectively, are rough projections; the cost of those operations would vary substantially depending on the method of harvesting and on the conversion technology employed (refer to discussion in Section 5.1). Practices and costs relating to sugarcane largely were used as the basis of this investigation; it is likely that optimization and improvement would take place following the transition from sugarcane that would increase the yield and reduce the cost of cultivating and harvesting banagrass; there appears to be sufficient opportunities for improving the cultivation and harvesting of banagrass so that the delivered cost of banagrass can be reduced by ~10%. Ongoing banagrass trials on Molokai suggest that the number of ratoon crops generated from each plant (seeded) crop could extend well beyond the level (five) assumed in this analysis without any significant reduction in yield (refer to discussion in Section 4.2); increasing the number of ratoon crops per plant crop from five to eight could result in a savings of >$4 per ton of biomass. Presently (refer to Section 5.3), federal renewable energy production credits for closed-loop biomass energy systems are equivalent to $0.015 per kWh; these credits probably would be available for the type of dedicated banagrass-for-electricity production system being considered here. The economic benefit from accelerated depreciation for closed-loop biomass energy systems depends on the level of investment made by the biomass producer/converter; no attempt is made to quantify the related savings. As stated earlier (Section 5.3), WSCo has negotiated or is presently negotiating with the federal and city governments to receive compensation for handling sewage effluent from the Schofield and Wahiawa wastewater treatment plants. Such compensation can help lower the effective cost of producing biomass feedstocks substantially; however, since no formal fee structure is in place at this writing, related savings are not shown in Table 5-5.

Table 5-5. Potential costs and savings in producing and converting biomass not included in Table 4-4 and Table 5-4.

Item	Unit Basis	$/unit	$/ton	$/kWh[a]
Additional Costs				
Landholding	acre-year	65.00[b]	3.03[c]	0.0025
Biomass Handling	ton	2.00[d]	2.00	0.0016
Biomass Dewatering	ton	4.00[d]	4.00	0.0033
Additional Savings				
Optimization (10% cost reduction)	ton	6.05[e]	6.05	0.0050
Increase Ratoon:Plant Crop to eight	ton	4.48[d]	4.48	0.0037
Federal Renewable Energy Credit	kWh	0.015	18.28[a]	0.0150
Accelerated Depreciation		Value not computed		
Handling of Sewage Effluent		Formal fee not established		

a Conversion efficiency (exportable electricity:biomass) = 1219 kWh/ton (average for two conversion technologies in Table 5-4).
b Typical value; costs within sugar industry range from nil to >$100/acre-year (refer to discussion in text).
c Assumed yield = 21.47 tons/acre-year.
d Estimate (refer to discussion in text).
e Plausible reduction in biomass production cost due to optimization of cultural practices, and harvesting and hauling operations for banagrass following transition from sugarcane.

5.5. Environmental, Social, and Energy-Policy Considerations

It is anticipated that replacing petroleum fuels with dedicated biomass feedstocks for electricity generation would have a favorable impact, overall, on the environment. Since the energy crop would be grown on land presently in sugarcane and since many of the agronomic processes being proposed for banagrass are very similar to sugarcane, the impact on the environment should not be greater than sugarcane currently being produced at WSCo. Moreover, since the field would be tilled only one-half (or less) as frequently as for sugarcane, and since the equipment being proposed for harvesting inflict less damage to the fields, soil disturbance and erosion should be less with banagrass than with sugarcane, thereby reducing non-point source pollution. With the harvesting system envisioned, wet cane cleaners would not be needed; therefore, waste water discharges would be much lower than presently at WSCo. Although particulate emissions from the power generation facility would be higher than those from an equivalent fuel oil based system, sulfur emissions should be lower; depending on the type of biomass used and abatement strategy employed, oxides of nitrogen may increase or decrease (research being performed by HNEI, such as that described by Ishimura, et al., 1994, is aimed at assessing the generation of nitrogenous species in biomass conversion processes). Carbon dioxide emissions would be offset in the growing of the biomass feedstock and, thus, effectively would be nil. Solid wastes would be discharged from combustion- or gasification-based systems in the form of char and ash; however, they generally are considered to be benign.

The environmental assessment for the Paia biomass gasifier facility submitted to the Office of Environmental Control of the State of Hawaii (Pacific International Center for High Technology Research, 1992) evaluated potential impacts of that facility to air quality and climatology, water quality, biological resources, public services and utilities, archaeological and cultural resources, health and safety, noise, traffic, land use, socioeconomics, and aesthetics. The assessment concluded that the various phases (construction and operation activities relating to biomass gasification, electricity generation, and even methanol synthesis) of the Paia project would not pose any known significant, short- or long-term, adverse impacts which could not be mitigated. To the contrary, the assessment found that the Paia project would provide significant environmental benefits that would supplement the anticipated energy and socioeconomic benefits. Although that environmental assessment was performed specifically for the Paia site, it is likely that given the similar rural nature of both communities, many of the findings for the Paia facility would apply to WSCo.

The field and conversion-facility operations, combined, could provide employment for more than 200 workers. Such a large labor force, combined with service industries needed to support biomass production and conversion, would provide significant employment opportunities for the north shore of Oahu. Furthermore, using biomass for electricity generation would help the State achieve its goal of reducing its reliance on imported fossil fuels.

6. Summary and Conclusions

The potential to generate electric power from biomass on the island of Oahu was investigated by examining the major technical and economic factors (e.g., land suitability and availability, energy-crop yield, delivery cost, and potential quantities and costs of electricity generated) associated with a single production unit, Waialua Sugar Company. While this investigation finds that biomass fuelstock delivered to a conversion facility would be more costly than fossil fuels presently being used to generate electricity on Oahu, energy-crop production credits and similar incentives in place or being considered, could make biomass-for-electricity production a viable resource for electric power generation on Oahu.

Salient findings of this investigation are summarized below:

1. Banagrass has significant potential for energy-crop production at WSCo.

   Banagrass and sugarcane require similar cultural practices and agronomic environments, and production and processing infrastructure. Banagrass yields have been unmatched by other grass and tree crops in numerous small and medium size trials in Hawaii; and previous technoeconomic evaluations of competing fiber crops grown on irrigated lands generally have found banagrass to be superior. For those reasons, and because most of the lands in sugarcane at WSCo have access to adequate supplies of irrigation water, and have terrain, soils, and climatic conditions that are well suited for banagrass production, banagrass appears to be the most suitable species for dedicated-biomass-for-electricity production and has been selected for this investigation.

   Several unit operations in banagrass production should be simpler and less costly than corresponding sugarcane production operations. The utilization of mechanical harvesters in conjunction with moderately sized transportation systems for banagrass instead of push-rakes and heavy sugarcane haulers likely will lead to less compaction and better ratoon stands. This would eliminate the need to plow and reseed the field after every harvest, and would facilitate ratooning. Consequently, soil preparation, seed production, planting, and weed control costs should be substantially lower for banagrass than for sugarcane. Also, because the equipment used for harvesting commercial banagrass for electricity generation could be the same as that used for cutting banagrass seed, those operations could be integrated, thus providing additional savings.

2. High yields of banagrass can be obtained in commercial biomass-for-electricity production.

   Previous research and demonstration programs, including an ongoing ten-acre trial on the island of Molokai, indicate that, given sufficient water and nutrients, commercial yields of 18 to 25 tons/acre-year (dry basis) of banagrass should be achievable at WSCo. An average commercial banagrass yield of 21.5 tons/acre-year was projected for WSCo, resulting in ~260,000 tons of biomass feedstock from WSCo's 12,000 acres. Even higher yields should be achievable if an aggressive yield-improvement program is launched.

3. The estimated cost of producing banagrass feedstock is $60 per ton (dry basis). Harvesting and transporting are the largest cost factors in producing biomass-for-energy.

The estimated cost of banagrass billets, FOB conversion-facility gate, is ~$60 per ton (dry basis). The major assumptions and basis of the banagrass feedstock cost projection are listed below:

- Banagrass acreage cultivated = 12,000 acres; average yield = 21.47 tons/acre-year.
- Nominal age at harvest = 8 months; number of ratoon crops per plant crop = 5.
- Rates for labor and employee benefits are same as present levels at WSCo.
- Costs for all banagrass field operations except harvesting and transporting extrapolated from 1989-1994 costs for corresponding sugarcane operations at WSCo (refer to Table 4-2 for specific assumptions).
- Costs for harvesting and transporting banagrass calculated from 1995-based cost estimates provided by L.A. Jakeway, HSPA (see Appendix).
- Ratio, administrative cost:total cost, is same as present level at WSCo (excluding sugarcane-related costs not relevant to banagrass production).
- Projected feedstock cost does not include land rent, feedstock handling, or dewatering costs, nor savings from federal renewable energy credit, accelerated depreciation, or sewage handling fee (refer to Table 5-5 for potential costs and savings relating to such factors).

Harvesting and transporting, combined, comprise 30% of the delivered cost of banagrass; factors often overlooked such as crop control, road maintenance, miscellaneous field operations, and general and administrative functions, combined, also represent ~30% of the feedstock cost. Within the major cost centers — soil preparation and planting, irrigation, fertilization, harvesting, and transporting — and in G&A, there appear to be sufficient opportunities for cost reduction (particularly in the form of higher worker productivity than assumed in this analysis) so that the cost of cultivating and delivering banagrass to the plant site can be reduced by ~10% (to ≤$55 per ton). The unit cost of the biomass feedstock can be reduced significantly by increasing crop yield and by increasing the number of ratoons obtainable from a single plant crop; e.g., increasing banagrass yield by 10% (without significantly increasing inputs) would result in a comparable reduction in the cost of the delivered feedstock; increasing the number of ratoon crops per plant crop from five to eight (without any significant reduction in yield) would reduce feedstock cost by >7%.

4. The amount of electricity exportable from banagrass at WSCo would be ~20–46 MW, depending on the capacity and the type of conversion technology employed.

If the existing moderate-pressure cogeneration facility at WSCo were retained, with only the turbogenerator and condenser replaced to accommodate reduced extraction, the present system would be capable of generating ~20 MW, consuming essentially all of the banagrass delivered to the conversion facility. Two alternative biomass-to-electricity technologies are considered in this investigation: (1) medium-pressure steam generation systems and (2) gas-turbine based combined-cycle systems. The biomass-energy-to-electricity conversion efficiency for the medium-pressure steam generation system is estimated to be 25% (1140 kWh/ton), while that for the gas-turbine based combined-cycle system is estimated to be 31% (1420 kWh/ton). After deducting parasitic requirements in the processing plant and the conversion facility, 36 MW would be exportable from the medium-pressure steam generation system and 46 MW from the gas-turbine based system; these export rates translate, respectively, to 280 and 350 million kWh annually.

5. The cost of generating electricity from the advanced, gas-turbine based system is projected to be ~$0.10 per kWh.

   The cost of generating electricity from banagrass for only a single conversion technology, the gas-turbine based combined-cycle system, is investigated. At a conversion efficiency of 31%, and feedstock cost of $60 per ton, the 12,000 acres of banagrass grown at WSCo annually would yield ~350 million kWh of exportable electricity, with a delivery rate of 46 MW, at an estimated cost of $0.101 per kWh (that total cost is comprised of feedstock and conversion components of $0.044 and $0.057 per kWh, respectively). Although the cost for installing and operating the conversion plant might conceivably be lower using less efficient technologies, any resultant savings in biomass-to-electricity conversion cost must be weighed against likely increases in the apparent cost of the fuelstock following reduced conversion efficiency. If the conversion efficiency can be increased beyond that assumed in this analysis, then the apparent cost of the fuelstock would decrease commensurately (likely resulting in an overall reduction in the cost of exportable power).

   Additional factors, not considered in this investigation, could improve the economic feasibility of generating electricity from banagrass. For example, the economics of biomass-for-electricity production would be enhanced substantially by the application of renewable energy production credits and accelerated depreciation presently available, and incentives being considered at this time by the federal government, for closed-loop biomass energy systems. Potential credits associated with reduced emissions and sewage handling, could improve further the feasibility of producing crops dedicated to energy conversion.

6. The potential for ash deposition in banagrass-fired power generation systems needs further investigation.

   Analytical results indicate that ash in banagrass contains high levels of potassium, chlorine, and silicon. These elements are known to promote ash deposition in boilers and other system components, which, in turn, degrade system performance. Banagrass ash contains much higher levels of potassium than sugarcane bagasse, thus posing a high slagging risk. Additional testing is needed to determine whether the high levels of ash in banagrass are problematical, and, if so, whether feedstock pretreatment processes such as leaching to remove water soluble alkalis might reduce the potential for slagging (HNEI has submitted a proposal to WSCo to assess the feasibility and benefits of leaching chopped banagrass to remove alkalis).

7. Banagrass production and conversion would have favorable social, environmental, and energy-policy impacts.

The combined field and conversion-facility operations for energy-crop power generation could provide employment for more than 200 workers; the direct labor force would be supported by an equal or greater number of indirect jobs. This would provide significant employment opportunities for the north shore of Oahu.

Environmental assessments have indicated that if proper mitigation strategies were adopted, biomass-for-electricity production would have negligible negative impact on the environment — soil disturbance and erosion are expected to be lower with banagrass than with sugarcane because fields would be plowed less frequently, and banagrass harvesting and transporting equipment would inflict less damage to the fields. Photosynthetic uptake of carbon dioxide by the growing banagrass makes this electricity-generation option carbon neutral.

Expansion of biomass power generation would help the State reduce its dependence on imported fossil fuels.

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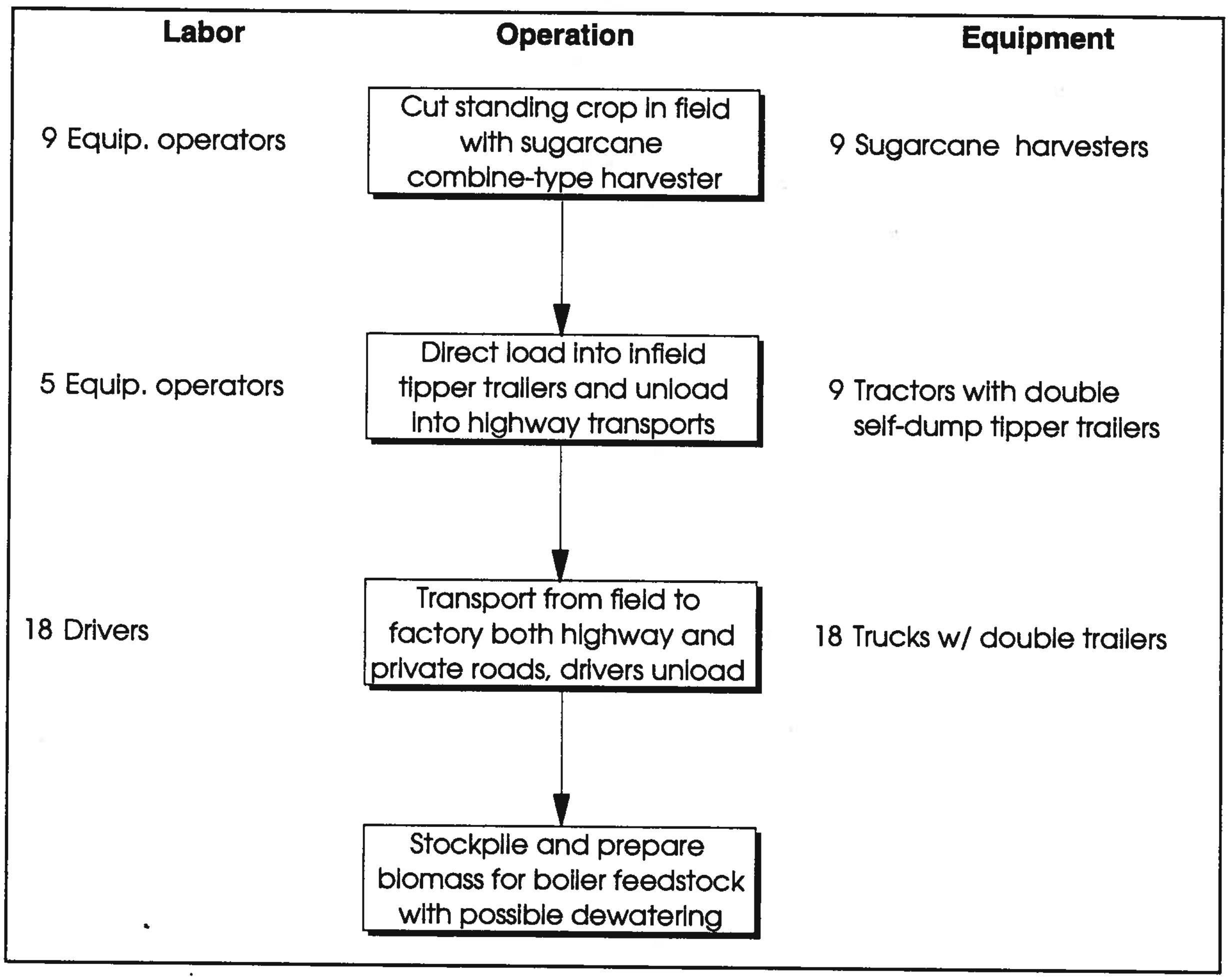
Appendix: Banagrass Harvesting and Delivery Costs

By Lee A. Jakeway, Hawaiian Sugar Planters' Association

Banagrass Harvest and Delivery System

Scenario 1: Short cane harvest system

Minimum labor and equipment requirements per work shift



Banagrass Harvesting and Delivery Costs

Scenario 1: Short cane harvest and delivery system

Summary of Harvesting/Transport Costs

Direct Costs	($/Ton, wet)	($/Ton, dry)
Labor		
Harvester operators	$0.43	$1.42
Tipper trailer operators	$0.19	$0.62
Truck/trailer operators	$0.82	$2.73
Supervision	$0.23	$0.77
Subtotal	$1.66	$5.54
Equipment Charges		
Claas harvester	$1.11	$3.70
Tipper trailers w/ tractor	$0.37	$1.23
Truck/trailer transport	$1.18	$3.95
Subtotal	$2.67	$8.88
Capital Recovery Cost Items		
Harvesters	$0.74	$2.46
Tipper trailers	$0.12	$0.39
Tractors for tipper trailers	$0.19	$0.63
Truck/trailers	$0.59	$1.96
Subtotal	$1.63	$5.44
Total Delivered Cost per Ton	$5.96	$19.87

Capital Requirements					
No.	Description	Unit Cost		Total	Annual C.R. Cost
12	Claas harvesters	$200,000		$2,443,426	$584,541
20	Tipper trailers	$30,000		$603,670	$92,591
10	4WD Tractor (150 hp)	$85,000		$855,199	$149,125
20	Truck/double trailer unit	$150,000		$3,036,929	$465,804
				$6,939,225	

Capital Recovery Factors used in Calculations					
		C.R. Factor		Int. Rate	
	Claas 1400 Harvester	0.2638		10%	Amortized over 5 years, 15% salvage value
	Tipper trailers	0.1628		10%	Amortized over 10 years, 15% salvage value
	4WD Tractor	0.1875		10%	Amortized over 8 years, 15% salvage value
	Truck/double trailer unit	0.1628		10%	Amortized over 10 years, 15% salvage value

Banagrass Harvesting and Delivery Costs

Scenario 1: Short cane harvest and delivery system

Assumptions Used

No.	Item Description	Value	Explanation/Reference
1	Yield of banagrass (short tons dry matter/acre/yr)	22	Given
2	Crop cycle (weeks)	32	R. Osgood memo to Y. Wang, 10/7/92
3	Area in cultivation (acres)	12,000	Existing Waialua Sugar Co. cultivated acreage
4	Cultivated area occupied by roads, irrig., etc. (%)	0%	Already discounted for assumed banagrass yield
5	Harvest loss (%)	10%	Assumes improved recovery from 2/95 Molokai harvest
6	Moisture at time of harvest (%)	70%	Given moisture at time of harvest
7	Actual harvester cutting productivity (short tons/machine-hr)	30	Based on 2/95 Molokai banagrass harvest results assuming no harvest loss
8	Number of paid labor days per year per worker	260	Given
9	Number of effective labor days per year	220	Less holidays, vacation, sick leave, etc.
10	Number of available equipment days per year	245	Less holidays, rainouts, etc.
11	Number of shifts per day	2	Given
12	Number of effective work hours per shift	7	Given
13	Factor increase for labor to match available equipment hours	1.1	Calculated
14	Bulk density of harvested banagrass with trash (lbs/cu. ft.)	8	Based on 2/95 Molokai results
15	Volume of trailer loads used for transport to factory (cu. ft.)	3168	J&L A2000 Cane Trailer product literature (volume for double-trailer unit)
16	Volume of in-field tipper (cu. ft.)	880	Cameco self high dump trailer product literature
17	No. of infield haul tractors per harvester	1	Given
18	No. of tipper units per tractor	2	Given
19	No. of potential equipment work hrs. per year	3430	Calculated
20	Round trip turn around time for transport trailers (min.)	60	Given
21	Harvest operator hourly wage rate	$8.11	Grade 6 wage rate in Haw'n sugar industry, excluding benefits
22	Tipper trailer operator hourly wage rate	$7.46	Grade 4 wage rate in Haw'n sugar industry, excluding benefits
23	Truck driver hourly wage rate	$7.79	Grade 5 wage rate in Haw'n sugar industry, excluding benefits
24	Supervisor hourly wage rate	$12.63	Based on annual salary of $26,275, excluding benefits, 260 days/yr
25	Harvester equipment operating cost ($/hr)	$30	Based on $100,000/yr operating cost for CLAAS
26	Tractor/infield tipper trailer operating cost ($/hr)	$10	Fuel and maintenance only
27	Truck/double trailer units($/hr)	$15	Used Hawaiian sugar industry data for haul cane truck-trailers
28	Equipment availability factor for Claas harvester	70%	Given
29	Equipment availability factor for tractor/tipper trailers	85%	Given
30	Equipment availability factor for truck/double trailer unit	90%	Given

Output Results

No.	Item Description	Value	Explanation
1	Dry matter yield (T/acre/yr, fiber basis)	22.00	Given from above yield, no losses included
2	Fresh weight yield (T/acre/yr)	73.33	With moisture added at time of harvest
3	Yield per crop (T/acre)	45.13	Based on annual yield and crop cycle
4	Annual potential fresh weight production	880,000	No area or harvester loss
5	Annual recovered fresh weight production (Tons)	792,000	Includes area and harvest losses
6	Annual dry matter production (T/acre/yr, dry basis)	237,600	Includes area and harvest losses
7	Hourly fresh weight delivery to boiler (t/hr)	90	Based on full-time operation, 365 days/yr
8	Hourly dry matter delivery to boiler (t/hr)	27	Based on full-time operation, 365 days/yr
9	Min no. of harvesters req'd to harvest crop	8.6	Based on 100% equipment availability and potential annual yield
10	Average infield tipper capacity(Tons)	7.04	Based on bulk density and volume of 2 in-field tipper units
11	No. of annual in-field haul trips req'd	56,250	Based on total tonnage and tipper capacity
12	Minimum turn-around-time for in-field tipper trailers (min.)	13.3	Based on maximum harvester production rate and tipper trailer capacity
13	Minimum no. of in-field haul tractors req'd	8.6	Based on minimum number of harvesters req'd
14	Minimum no. of in-field tipper trailers required	17.1	Based on minimum number of harvesters and in-field tractors req'd
15	Average trailer load capacity (Tons)	13	Based on bulk density and volume of double trailer haul unit
16	No. of annual transport trailer trips req'd	62,500	Based on total recovered tonnage and trailer haul capacity
17	Minimum minutes required per trailer trip	3.3	Assuming 1 double trailer operating fulltime during available operating hrs.
18	Minimum no. of truck/trailers required	18	Based on given roundtrip time and minimum time for one truck-trailer
19	No. of harvesters req'd including spares	12	Based on production rate and equipment availability
20	No. of in-field tipper trailers req'd including spares	20	Based on given requirement for harvester and equipment availability
21	No. of tractors req'd to operate tipper trailers	10	Based on number of tipper trailers per tractor and equipment availability
22	No. of truck double- trailers req'd including spares	20	Based on minimum number and equipment availablity
23	Total manning for harvester operators	20	Based on equipment production rates and no. of daily shifts
24	Total manning for tipper/trailer tractor operators	9	Assumed that truck driver labor will assist here
25	Total manning for truck drivers	40	Based on equipment production rates and no. of daily shifts
26	Total supervisory labor	7	Worker to supervisor ratio used was 10 to 1
27	Total daily manning	77	

Banagrass Harvest and Delivery System

Scenario 2: Forage harvester and delivery system

Minimum labor and equipment requirements per work shift

Labor	Operation	Equipment
9 Equip. operators	Cut standing crop in field with self-propelled forage harvester	9 Forage harvesters
5 Equip. operators	Direct load into infield tipper trailers and unload into highway transports	9 Tractors with double self-dump tipper trailers
16 Drivers	Transport from field to factory both highway and private roads, drivers unload	16 Trucks w/ double trailers
	Stockpile and prepare biomass for boiler feedstock with possible dewatering	

Banagrass Harvesting and Delivery Costs

Scenario 2: Forage harvester and delivery system

Summary of Harvesting/Transport Costs

Direct Costs	($/Ton, wet)	($/Ton, dry)
Labor		
Harvester operators	$0.40	$1.35
Tipper trailer operators	$0.18	$0.59
Truck/trailer operators	$0.69	$2.30
Supervision	$0.20	$0.68
Subtotal	$1.48	$4.92
Equipment Charges		
Forage harvester	$1.32	$4.39
Tipper trailers w/ tractor	$0.35	$1.17
Truck/trailer transport	$0.99	$3.29
Subtotal	$2.65	$8.84
Capital Recovery Cost Items		
Harvesters	$0.82	$2.72
Tipper trailers	$0.11	$0.37
Tractors for tipper trailers	$0.18	$0.59
Truck/trailers	$0.49	$1.63
Subtotal	$1.59	$5.32
Total Delivered Cost per Ton	$5.72	$19.08

Capital Requirements					
No.	Description	Unit Cost		Total	Annual C.R. Cost
14	Forage harvesters	$200,000		$2,850,664	$681,964
20	Tipper trailers	$30,000		$603,670	$92,591
10	4WD Tractor (150 hp)	$85,000		$855,199	$149,125
18	Truck/double trailer unit	$150,000		$2,671,373	$409,735
				$6,980,906	
Capital Recovery Factors used in Calculations					
		C.R. Factor		Int. Rate	
	Forage harvester	0.2638		10%	Amortized over 5 years, 15% salvage value
	Tipper trailers	0.1628		10%	Amortized over 10 years, 15% salvage value
	4WD Tractor	0.1875		10%	Amortized over 8 years, 15% salvage value
	Truck/double trailer unit	0.1628		10%	Amortized over 10 years, 15% salvage value

Banagrass Harvesting and Delivery Costs

Scenario 2: Forage harvester and delivery system

Assumptions Used

No.	Item Description	Value	Explanation/Reference
1	Theoretical yield of banagrass (short tons dry matter/acre/yr)	22	Given
2	Crop cycle (weeks)	32	R. Osgood memo to Y. Wang, 10/7/92
3	Area in cultivation (acres)	12,000	Existing Waialua Sugar Co. cultivated acreage
4	Cultivated area occupied by roads, irrig., etc. (%)	0%	Already discounted for assumed banagrass yield
5	Crop harvest loss (%)	5%	Assumes improved recovery from 2/95 Molokai harvest
6	Moisture at time of harvest (%)	70%	Inverse of average fiber percentage as reported by R. Osgood, 10/7/92
7	Actual harvester cutting productivity (short tons/machine-hr)	30	Same as sugarcane harvester
8	Number of paid labor days per year per worker	260	Given
9	Number of effective labor days per year	220	Less holidays, vacation, sick leave, etc.
10	Number of available equipment days per year	245	Less holidays, rainouts, etc.
11	Number of shifts per day	2	Given
12	Number of effective work hours per shift	7	Given
13	Factor increase for labor to match available equipment hours	1.1	Calculated
14	Bulk density of harvested banagrass with trash (lbs/cu. ft.)	12	Assumed 50% higher than sugarcane harvester
15	Volume of trailer loads used for transport to factory (cu. ft.)	3168	J&L A2000 Cane Trailer product literature (volume for double-trailer unit)
16	Volume of in-field tipper (cu. ft.)	880	Cameco self high dump trailer product literature
17	No. of infield haul tractors per harvester	1	Given
18	No. of tipper units per tractor	2	Given
19	No. of potential equipment work hrs. per year	3430	Calculated
20	Round trip turn around time for transport trailers (min.)	75	Given
21	Harvest operator hourly wage rate	$8.11	Grade 6 wage rate in Haw'n sugar industry, excluding benefits
22	Tipper trailer operator hourly wage rate	$7.46	Grade 4 wage rate in Haw'n sugar industry, excluding benefits
23	Truck driver hourly wage rate	$7.79	Grade 5 wage rate in Haw'n sugar industry, excluding benefits
24	Supervisor hourly wage rate	$12.63	Based on annual salary of $26,275, excluding benefits, 260 days/yr
25	Harvester equipment operating cost ($/hr)	$38	Assumed 25% higher operating costs compared to sugarcane harvester
26	Tractor/infield tipper trailer operating cost ($/hr)	$10	Fuel and maintenance only
27	Truck/double trailer units($/hr)	$15	Used Hawaiian sugar industry data for haul cane truck-trailers
28	Equipment availability factor for forage chopper	60%	Assumed higher downtime compared to sugarcane harvester
29	Equipment availability factor for tractor/tipper trailers	85%	Given
30	Equipment availability factor for truck/double trailer unit	90%	Given

Output Results			
No.	Item Description	Value	Explanation
1	Actual yield (T/acre/yr, fiber basis)	22.00	Given from above yield, no losses included
2	Fresh weight yield (T/acre/yr)	73.33	With moisture added at time of harvest
3	Yield per crop (T/acre)	45.13	Based on annual yield and crop cycle
4	Annual potential fresh weight production	880,000	No area or harvester loss
5	Annual recovered fresh weight production (Tons)	836,000	Includes area and harvest losses
6	Annual dry matter production (T/acre/yr, dry basis)	250,800	Includes area and harvest losses
7	Hourly fresh weight delivery to boiler (t/hr)	95	Based on full-time operation, 365 days/yr
8	Hourly dry matter delivery to boiler (t/hr)	29	Based on full-time operation, 365 days/yr
9	Min no. of harvesters req'd to harvest crop	8.6	Based on 100% equipment availablity and potential annual yield
10	Average infield tipper capacity(Tons)	10.56	Based on bulk density and volume of 2 in-field tipper units
11	No. of annual in-field haul trips req'd	39,583	Based on total tonnage and tipper capacity
12	Minimum turn-around-time for in-field tipper trailers (min.)	18.9	Based on maximum harvester production rate and tipper trailer capacity
13	Minimum no. of in-field haul tractors req'd	8.6	Based on minimum number of harvesters req'd
14	Minimum no. of in-field tipper trailers required	17.1	Based on minimum number of harvesters and in-field tractors req'd
15	Average trailer load capacity (Tons)	19	Based on bulk density and volume of double trailer haul unit
16	No. of annual transport trailer trips req'd	43,981	Based on total recovered tonnage and trailer haul capacity
17	Minimum minutes required per trailer trip	4.7	Assuming 1 double trailer operating fulltime during available operating hrs.
18	Minimum no. of truck/trailers required	16	Based on given roundtrip time and minimum time for one truck-trailer
19	No. of harvesters req'd including spares	14	Based on production rate and equipment availability
20	No. of in-field tipper trailers req'd including spares	20	Based on given requirement for harvester and equipment availability
21	No. of tractors req'd to operate tipper trailers	10	Based on number of tipper trailers per tractor and equipment availability
22	No. of truck double- trailers req'd including spares	18	Based on minimum number and equipment availablity
23	Total manning for harvester operators	20	Based on equipment production rates and no. of daily shifts
24	Total manning for tipper/trailer tractor operators	9	Assumed that truck driver labor will assist here
25	Total manning for truck drivers	36	Based on equipment production rates and no. of daily shifts
26	Total supervisory labor	7	Worker to supervisor ratio used was 10 to 1
27	Total daily manning	72	