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TASK 4 ALTERNATIVE ENERGY SYSTEMS
4.7 Alternative Biofuels Development:
Production, Harvesting, and Handling Assessment

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3.0 Executive Summary

This report is the third of a six-part Biofuels Assessment\(^1\) (“Assessment”); it is Activity 3. The purpose of the Assessment is to advance the development of alternative fuel production facilities within the state of Hawaii through research. The research conducted in this undertaking focuses on facilities that would utilize biomass conversion technologies to produce renewable liquid fuels, including ethanol, renewable diesel, and renewable jet fuel for commercial and military use. To facilitate the application of its findings, the Assessment is structured around an examination of the transition of an operating sugar plantation, the Hawaiian Commercial & Sugar Company\(^2\) (“HC&S”) of Puunene, Maui, to a combined sugar and liquid biofuel producing farm, with the flexibility to adjust the ratio between sugar and biofuel production as future circumstances arise.

The flexibility and economics of various production, harvesting, and handling methodologies will be an important component of an HC&S transition to an energy farm. Activity 3 is an assessment of the best practices and equipment required for the production, harvesting, and handling of crops identified as suitable for biofuel conversion at HC&S. These crops are identified in Activity 2 (Crop Assessment)\(^3\) as follows:

1) Sugarcane  
2) Type I energycane  
3) Type II energycane  
4) Banagrass  
5) Giant leucaena  
6) Eucalyptus

As HC&S has expressed a strong preference towards crops and practices that have been proven in commercial production and harvesting, particularly in central Maui and with farming history and research in Hawaii, this Executive Summary is limited to sugarcane and banagrass. Since HC&S is an ongoing sugar operation, and must consider the practical aspects of a transition to crops other than sugarcane, this assumption is reasonable in the near term. Other crops on the Activity 2 Short List (banagrass\(^4\), giant leucaena) would require years of development prior to commercial-scale adoption, as they are not grown commercially in Hawaii. A transition to energycane may arguably take five years to initial commercial planting and 10 years to full-scale adoption. Development of crops other than sugarcane and energycane could require a significantly longer transition.

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\(^1\) See Section 3.1.1 for additional information on the Biofuel Assessment Project.  
\(^2\) Additional information on HC&S is provided in Section 3.1.2.  
\(^3\) The “Activity 2 (Crop Assessment)” is the second part of the six-part Biofuels Assessment. See “Section 3.1.1 Biofuels Assessment; Activities 1 through 5, Final Report” for additional information.  
\(^4\) This report’s findings for banagrass are highlighted in this Executive Summary, despite its transition requirements, because of its potential as a viable feedstock at HC&S after a transition.
Sugarcane

Table 3-10 summarizes some key outputs that generally characterize a current crop production system utilized in Hawaii. Approximately 200,000 tons of sugar can be produced from an area of 16,350 acres harvested per year, on a two-year cropping system. This equates to a nominal productivity of 5.67 tons of sugar (t_s) per farmed acre per year (after allowing for area set aside for seedcane), or an “agronomic yield” of approximately 6.5 t_s per harvested acre after correcting for average crop age and area harvested for milling. The crop-cycle is typically two years between replants, with approximately 20% of the harvested crop being ratooned. Analysis of the crop production and harvesting systems indicate mechanically aggressive processes.

<table>
<thead>
<tr>
<th>Table 3-10: Summary of key parameters relating to a production system based on current practices in the Hawaiian Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmed Area (acres)</td>
</tr>
<tr>
<td>Annual Harvest (acres)</td>
</tr>
<tr>
<td>Estimated Product Tonnage Transported to Mill (t/acre)</td>
</tr>
<tr>
<td>Annual Fiber Production (dry, ash free) in Bagasse</td>
</tr>
<tr>
<td>Annual Sugar Production (t)</td>
</tr>
<tr>
<td>Annual Sugar Production/Gross Farmed Acre</td>
</tr>
</tbody>
</table>

The yields of recovered sugar on productivity per farmed acre per year are lower than yields achieved on some other large scale industries. All harvest and transport systems have losses, and mechanization usually equates to a balance between losses and costs. While arguably low cost, available information indicates that the Hawaiian harvest and transport system and associated washing plants result in only approximately 55% of the sucrose produced by the crop being recovered at the mill. These recoveries are significantly lower than recoveries achieved with other mechanized systems (typically 70 to 80%, reducing as crop size increases) and substantially less than manual based systems (typically 80 to 90%). This substantially impacts on recovered sugar yields in Hawaii relative to other industries, and thus industry profitability. This matter is discussed further in Section 3.3.4.5 Sugar Recovery for Current Harvest and Milling System.

Aside from the impact of management decisions on crop inputs, yields at HC&S have been stable for many years. Water availability is named by staff as the most significant factor impacting on crop productivity. Despite this nominally stable productivity,

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5 Throughout this report, the term “industry” or “sugar industry” refers to sugar operations outside of Hawaii.
international research indicates that it is very highly probable that the current crop production system has resulted in reducing soil organic matter levels and increasing levels of plant parasitic organisms in the soil. While these factors do not necessarily negatively impact on yields under high levels of inputs, the impact on yield under sub-optimal conditions is much more dramatic (Garside et al.\textsuperscript{6}). These issues need further investigation.

The introduction of green cane harvesting (utilizing current harvesting, cane cleaning and milling strategies) is aimed towards increasing the total value\textsuperscript{7} of the product being produced, while minimizing the changes required to the overall crop production, harvesting and processing system. Initial analysis indicates that a move to green cane harvesting without other changes\textsuperscript{8} would result in the following.

- No significant change to agricultural production methods.
- An increase in harvesting and cane transport costs in the order of 50%, to a cost of approximately $826 per acre per harvest.
- An elimination of losses associated with pre-harvest firing of the crop, which is more than offset by the reduction in sucrose recovery, because of the increased trash levels being processes. Sugar production would fall by approximately 9%.
- A significant reduction in harvest rate required to supply the mill, to approximately 70% of the burned cane rate, with a corresponding and unsustainable increase in season-length.
- Fiber production would increase by approximately 100,000 tons per year, with all of the additional fiber passing through the milling tandems. Significant loss of fiber is also anticipated through the (unmodified) cane laundry.

The incorporation of Olsen Rolls in the washing plant at an assumed efficiency level, along with strategies to maximize trash recovery, would produce the following results.


\textsuperscript{7} Increasing the value of the product may be assumed to correspondingly increase profitability.

\textsuperscript{8} A “move to green cane harvesting without other changes” includes the current practice of planting two-year sugarcane.
Sucrose recovery would be higher than with the unmodified mill and unburned cane. However total sugar recovery is initially estimated to be 5% lower than with production from current burned cane strategies.

The milling rate would improve by approximately 20% relative to the green cane scenario, resulting in a new season-length of approximately 275 days, or 13% longer than the burnt cane season-length.

Fiber production from both bagasse and cane trash would increase from approximately 230,000 tons to approximately 360,000 tons.

The option of developing strategies for the utilization of chopper harvesters for harvesting unburned crops under Hawaiian conditions involves very significant changes, including the following.

- Major changes to current agricultural production methods, including the move to annual or quasi-annual cropping. This would involve significant changes to all aspects of crop management.

- The requirement for significant smoothing of fields and removal of rocks. The most viable strategy would be the adoption of farming systems based on the concept of controlled traffic and minimum tillage to “manage” the rock problem after the initial rock removal programs.

- Despite these issues, the move to minimum tillage in conjunction with the typical ratoon-cycles associated with annual cropping would see a reduction in tillage cost per ton cane to approximately 20% of current levels and a reduction in planting costs to 30 to 40% of current levels.

- Additional benefits would be the increase in land available for commercial production as the area currently used for seedcane will be substantially reduced.

- The costs of chopper harvesting will be substantially higher than the cost of the current harvesting system with the annual cost of the harvest and transport operation being in the order of $28,000,000. This is almost double the cost of an alternate system of utilizing the current harvesting system with green cane, and over three times the cost of the current burned cane harvesting system.

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9 For the purposes of this report, “green harvesting” and “chopper harvesting” are used interchangeably.
Against this increase in cost of the harvesting operation is a predicted substantial increase in sugar recovery relative to the current burned cane and potential green cane harvesting options. Table 3-26 presents a summary of the anticipated sucrose recovery and fiber recovery of the “one year” chopper harvested cane option against the current burned cane and potential green cane production systems. The reduction in losses at the mill associated with the chopper harvesting and dry cleaning of unburned cane relative to the current harvesting strategies is the primary driver for the very significant increase in sucrose recovery.
Table 3-26: Product mass flow and recoverable sucrose flow from the field through the cleaning and milling processes

<table>
<thead>
<tr>
<th></th>
<th>Burnt Cane Washed</th>
<th>Green Cane Washed</th>
<th>Wash + Olsen</th>
<th>1-year Cane Chopper Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cane in Field Prior to Harvest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoverable sucrose in stalk (%)</td>
<td>16.4%</td>
<td>16.9%</td>
<td>16.9%</td>
<td>16.05%</td>
</tr>
<tr>
<td>Tons clean stalk/acre</td>
<td>107</td>
<td>107</td>
<td>107</td>
<td>50</td>
</tr>
<tr>
<td>Tons recoverable sugar (t/acre)</td>
<td>17.54</td>
<td>18.08</td>
<td>18.08</td>
<td>8.05</td>
</tr>
<tr>
<td>Sucrose at Delivery for Pre-cleaning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoverable sucrose in clean stalk (%)</td>
<td>16.2%</td>
<td>16.8%</td>
<td>16.8%</td>
<td>16.05%</td>
</tr>
<tr>
<td>Tons stalk/acre</td>
<td>97.4</td>
<td>97.4</td>
<td>97.4</td>
<td>42.6</td>
</tr>
<tr>
<td>Tons sugar/acre</td>
<td>15.8</td>
<td>16.4</td>
<td>16.4</td>
<td>6.83</td>
</tr>
<tr>
<td>Sucrose Entering Milling Train after Washing/Trash Separation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoverable sucrose in stalk (%)</td>
<td>13.6%</td>
<td>14.1%</td>
<td>14.1%</td>
<td>16.05%</td>
</tr>
<tr>
<td>Tons/stalk/acre</td>
<td>91.5</td>
<td>91.5</td>
<td>88.6</td>
<td>42.5</td>
</tr>
<tr>
<td>Tons sugar/acre</td>
<td>12.5</td>
<td>12.9</td>
<td>12.5</td>
<td>6.81</td>
</tr>
<tr>
<td>Sugar Recovered in Mill</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tons sugar / acre recovered</td>
<td>12.2</td>
<td>11.2</td>
<td>11.6</td>
<td>6.62</td>
</tr>
<tr>
<td>Sugar losses: Field to milling train</td>
<td>29%</td>
<td>29%</td>
<td>31%</td>
<td>15%</td>
</tr>
<tr>
<td>Factory sugar losses: Sugar lost between entering milling train and final recovery</td>
<td>2%</td>
<td>13%</td>
<td>7%</td>
<td>3%</td>
</tr>
<tr>
<td>Field and factory loss of recoverable sugar</td>
<td>33%</td>
<td>38%</td>
<td>36%</td>
<td>18%</td>
</tr>
<tr>
<td>Total sugar recovery (tons/year)</td>
<td>199,874</td>
<td>182,799</td>
<td>190,377</td>
<td>229,709</td>
</tr>
<tr>
<td>Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber in cane entering milling train (%)</td>
<td>15.4%</td>
<td>22.1%</td>
<td>18.2%</td>
<td>16.3%</td>
</tr>
<tr>
<td>Fiber in bagasse (t/acre)</td>
<td>14.05</td>
<td>20.2</td>
<td>16.12</td>
<td>6.91</td>
</tr>
<tr>
<td>Fiber from Olsen Rolls (t/acre)</td>
<td></td>
<td>5.9</td>
<td></td>
<td>4.07</td>
</tr>
<tr>
<td>Total fiber recovered (t/acre)</td>
<td>14.05</td>
<td>20.19</td>
<td>22.01</td>
<td>10.98</td>
</tr>
<tr>
<td>Total fiber recovery (tons)</td>
<td>229,740</td>
<td>330,040</td>
<td>359,800</td>
<td>370,100</td>
</tr>
<tr>
<td>Milling Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acres/hr for mill @ 50t/hr Fiber</td>
<td>3.6</td>
<td>2.5</td>
<td>3.1</td>
<td>7.23</td>
</tr>
<tr>
<td>Harvest length @ 80% time efficiency</td>
<td>236</td>
<td>341</td>
<td>275</td>
<td>243</td>
</tr>
</tbody>
</table>

10 The tons sugar/acre at delivery is the pre-harvest tons sugar/acre less direct and indirect harvesting losses.
A significant additional benefit of a move to chopper harvesting and dry trash separation at the mill is the elimination of both the direct cost of the current cane cleaning plant and the loss of productivity associated with the area required for water and waste disposal.

**Banagrass**

Banagrass, a cultivar of *Pennisetum purpureum*, is a highly productive “tall grass”, which is increasingly being assessed as an energy crop for either direct combustion or for a range of conversion technologies.

- Banagrass is an all-cellulose alternative to sugarcane.
- The crop production methods utilized for banagrass and other energy grasses will be similar to the methods discussed for annual harvest sugarcane. Based on limited knowledge to-date, it is likely that the replant period may be increased as the crops typically ratoon aggressively.
- The environmental sustainability of the crop is anticipated to be very good. This is because there are very limited periods in which there is no ground cover, and it is anticipated that there will be significant periods between replant operations. Therefore, the harvest operation results in significant “stubble” and the soil is seldom bare and exposed to wind or rain.
- The preferred harvesting method is the use of forage harvesters, due to operational considerations associated with the terrain where the banagrass would be grown, load densities, and crop stool damage.
- The harvesting cost of banagrass is assumed to be marginally lower than the harvesting cost of sugarcane.

Further, as discussed in the Activity 2 report:

- In many aspects, banagrass is as ideal a crop for the production of cellulosic biomass; it is highly productive, can be grown on long cropping cycles, and has the ideal architecture for delivery to a billet or forage harvester.
- Banagrass has one major drawback in that it is classified as invasive by seed.
• An alternative to banagrass is a Pennisetum cultivar with purple leaf-color and the complete absence of flowers and seed. In other aspects, it is similar to banagrass.

• Another alternative is a hybrid of banagrass with pearl millet which is sterile.
3.1 **Introduction – Biofuels Assessment**

This report is the third of a six-part Biofuels Assessment (“Assessment”). The purpose of the Assessment is to advance the development of alternative fuel production facilities within the state of Hawaii through research. The research conducted in this undertaking focuses on facilities that would utilize biomass conversion technologies to produce renewable liquid fuels, including ethanol, renewable diesel, and renewable jet fuel for commercial and military use. To facilitate the application of its findings, the Assessment is structured around an examination of the transition of an operating sugar plantation, the Hawaiian Commercial & Sugar Company (“HC&S”) of Puunene, Maui, to a combined sugar and liquid biofuel-producing farm. The outcome of this Assessment is a biofuel model that may be adapted for the development of other alternative fuel production facilities within the State. The Assessment is organized into the following five Activities and a Final Report, as described next in Section 3.1.1.

3.1.1 **Biofuels Assessment; Activities 1 through 5, Final Report**

The Assessment is organized into the following five Activities and a Final Report.

**Activity 1: Site Survey**

Activity 1 is a survey of the conditions specific to the HC&S plantation, and the preparation of a comprehensive graphical mapping and tabular database.

**Activity 2: Crop Survey and Crop Assessment**

Activity 2 is a survey of available literature to identify crops suitable for use in the production of biofuels at HC&S, followed by a closer examination of crops with the potential to serve as biofuel feedstock. The Activity includes the determination of the optimal crop or mix of crops that will result in the most cost effective and maximum crop yields for biofuels production at the HC&S plantation.

**Activity 3: Production, Harvesting, and Handling Assessment**

Activity 3 is an assessment of the best practices and equipment required for the production, harvesting, and handling of the selected feedstocks with potential applicability to HC&S.
Activity 4: Feedstock Assessment, Processing Assessment, and Waste Handling

Activity 4 is additional analysis of the crops selected in Activity 2, examining their suitability for HC&S biofuel production, followed by the identification of thermochemical, biochemical, and hybrid conversion technologies that can be used to convert the selected feedstocks into usable, sustainable, high-value energy products. This Activity includes a detailed evaluation of one conversion pathway.

Activity 5: Biofuel Model

Activity 5 is the development of an illustrative Biofuel Model to demonstrate the economic viability of an HC&S transition from an operating sugar plantation to an energy farm capable of commercial-scale, next-generation, advanced renewable biofuels production.

Final Report: This report integrates the five Activities into a comprehensive plan for commercial-scale production of renewable fuel production at HC&S.

The flow of information among the five Activities is as represented in Figure 3-1.
3.1.2 Background - Hawaiian Commercial & Sugar Company

HC&S is an integrated grower and processor of sugarcane on over 35,000 contiguous acres in the central valley of Maui. It is bordered by the Pacific Ocean on the north, the West Maui Mountains on the west, and by Haleakala on the east. (See Figure 3-2.) Using state-of-the-art agronomy practices, HC&S cultivates two-year sugarcane, unique to Hawaii, and its yields equate to those achieved in some of the other highest yielding estates of similar size in the world. HC&S produces premium raw sugar products that are marketed worldwide under the Maui Brand name; approximately 200,000 tons of raw sugar (equivalent) and 65,000 tons final molasses.

In addition to its extensive sugar operations, electrical power generation and production of process steam from the burning of bagasse are by-products of sugar production. The steam is used to power the cane cleaner and sugarmill, and to evaporate water from the sugarcane juice. The electrical power is generated though HC&S’s hydroelectric and cogeneration facilities, with bagasse as the primary fuel to its cogeneration facilities. HC&S generates about 200,000 MWH of electricity per year. The electricity is used for mill operations, pumping irrigation water, and sales of about 95,000 MWH to the county’s public utility, the Maui Electric Company.

HC&S has been in operation for over 125 years. Currently, it is the only sugar plantation remaining in Hawaii, and has over 800 employees. It is a part of Alexander and Baldwin, Inc.’s Agribusiness group.

The crops selected for production, harvesting and handling review in this report were determined in Activity 2 of this Assessment. Based on that selection, assumptions related to HC&S operations and Activity 3 are as follows.

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Figure 3-2: Location of HC&S

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1) One of HC&S’s strengths is its experience and expertise in the sugar industry. To the extent sugar prices remain relatively high, it is assumed that the crops or mix of crops selected as feedstock must support the production of both

- crystalline raw sugar for conversion to refined and specialty sugar
- ligno-cellulosic fiber for conversion to advanced liquid biofuel(s)

Since HC&S is an ongoing sugar operation, and must consider the practical aspects of a transition to crops other than sugarcane, this assumption is reasonable in the near term. Other crops on the Activity 2 Short List (banagrass and giant leucaena) would require years of development prior to commercial-scale adoption, as they are not grown commercially in Hawaii. A transition to energycane may arguably take five years to initial commercial planting and 10 years to full-scale adoption. Development of crops other than sugarcane and energycane could require a significantly longer transition.

2) Based on its operating experience, HC&S has a preference towards perennial crops that are harvested infrequently.

3) A significant consideration in a transition to alternate production, harvesting, and handling practices is an understanding of the effect that operating practices may have on the environment and the community.

HC&S is one of Maui’s largest businesses and has a long history of community leadership and responsible environmental stewardship. Any change in its operations will be highly visible and has a potential to generate public concerns. Therefore, environmental and community matters must be considered in crop selection and operating practices.

4) At the time this Assessment was prepared, HC&S stated that it was not interested in the production of ethanol.

HC&S would only consider cane juice-to-ethanol production if this is financially more beneficial compared to raw sugar production, and if there is a viable technical solution to vinasse disposal.

5) HC&S has a strong preference towards crops and practices that have been proven in commercial production and harvesting, particularly in central Maui, with farming history and research in Hawaii.
3.2 Activity 3 – Production, Harvesting, and Handling Assessment

3.2.1 Objective

The flexibility and economics of various production, harvesting, and handling methodologies will be an important component of HC&S’s transition to an integrated sugar and energy farm. The objective of Activity 3 is to assess those components and building upon the work done in the earlier Activities in this Biofuels Assessment. Activity 1 (Site Survey) provided information regarding the HC&S site. Activity 2 (Crop Assessment) identified a short list of crops (“Short List”) suitable for biofuel conversion at HC&S. Activity 3 covers the production, harvesting, and handling of crops on the Short List. The Short List of crops is as follows:

1) Sugarcane 4) Banagrass
2) Type I energycane 5) Giant leucaena
3) Type II energycane 6) Eucalyptus

The Activity 3 assessment will:

1) Assess farming practices and equipment requirements for the production of feedstocks with potential applicability to HC&S

2) Address sugarcane and sugarcane trash, including requirements for transitioning from burnt-cane push-rake harvesting to green harvesting

3) Provide cost data to compare production, harvesting, and handling alternatives

This report includes one appendix; Appendix 3-A. It provides a brief background on lead researcher Chris Norris, Principal Consultant with Norris Energy Crop Technology of Brisbane, Queensland, Australia. (See www.norrisect.com.12)

3.2.2 Process

Since there is substantial similarity in production, harvesting, and handling considerations among the crops on the Short List, and there is much interest in the harvesting practices of biannually-harvested (“two-year”) sugarcane, this report is organized as follows.
Section 3.3 Crop Option #1: Two-year Sugarcane, Burned for Harvest

This section briefly describes HC&S’s current production and harvesting practices, including burnt-cane push-rake harvesting. Sugar losses associated with harvesting and the cane cleaning process are also assessed.

Section 3.4 Crop Option #2: Two-year Sugarcane, Unburned for Harvest

This section covers possible modifications to transition HC&S from its current harvesting practices to a system of green cane harvesting. The impact of this modification on costs and on both fiber and sucrose recovery are also assessed.

Section 3.5 Crop Option #3: One-year Sugarcane and Type I Energycane, Mechanically Harvested

This section discusses possible changes to the HC&S crop production system, as well as the harvesting system appropriate for sugarcane and Type I energycane; typically on an annual basis, although longer or shorter crop-cycles are possible.

Section 3.6 Crop Option #4: Type II Energycane and Energy Grasses (including Banagrass), Mechanically Harvested on an Annual or Shorter Basis

Type II energycane and banagrass (for supplemental fiber) were identified in Activity 2 as alternatives to sugarcane. This section addresses issues related to the production and mechanical harvesting of these crops.

Section 3.7: Crop Option #5: Tree Crops (including Giant Leucaena and Eucalyptus), Mechanically Harvested

Trees, particularly giant leucaena and eucalyptus, may provide supplemental fiber for feedstock, if needed. This section covers production issues and strategies for the mechanized harvesting of trees.

3.2.3 Background

Traditionally, the Hawaiian sugar industry (“Industry” or “Hawaiian Industry”) has focused on the production of sugarcane as a monoculture, for the sole purpose of the production of crystalline sugar. The current sugarcane production system in Hawaii is
highly mechanized; however its mechanization strategies are different from the strategies adopted by virtually any other country’s sugar industry\textsuperscript{13} around the world.

A decline in labor availability and subsequent high labor costs forced the Hawaiian Industry into early development and adoption of mechanization. Ironically, this situation led to the Hawaiian Industry developing along a mechanization strategy, which has subsequently not been followed by any other sugar production industry. The reasons for this divergence in strategy are manyfold. Two primary drivers for the strategy adopted by the Hawaiian Industry at the time can be argued to be as follows.

1) Crop yields at harvest in the Hawaiian Industry were higher than in virtually any other sugar industry worldwide, by virtue of:

- Growing conditions which facilitated high rates of crop growth throughout the year
- The typical age of the cane, about 24 months at harvest, was greater than in most other sugar industries

The reasons for the longer crop-cycle were related to the year-around growth of sugarcane with no distinct cool, dry harvest season, and with the coolest conditions occurring in the wettest season. This is the exact opposite of what occurs in other important producing countries.

2) Topography and conditions in many of the fields were not compatible with many of the strategies being developed in other sugarcane growing countries.

The harvesting systems developed in Hawaii have been well documented and typically incorporate:

- Pre-harvest burning followed by pushing the cane into windrows, typically with modified industrial earthmoving equipment; typically a “D8” tracklayer tractor fitted with a rake instead of the blade
- Loading the windrowed cane with large industrial loaders (initially cable-grab systems, but more recently hydraulically-actuated units)

\textsuperscript{13} Throughout this report, the term “industry” or “sugar industry” refers to sugar operations outside of Hawaii.
- Transporting of the cane to the mill in high capacity, specialized vehicles on a dedicated road system

- Cleaning the cane in cane washing systems to remove soil and rocks prior to the shredding and extraction processes normally undertaken

By nature, this harvesting strategy, especially with shallow rooting compounded by the watering profile created by drip irrigation, resulted in high mortality/removal of the cane stool. As a result, after the harvesting operation, “gap filling” on a large scale, effectively approximating a replant, was required to achieve an adequate population for acceptable ratoon performance. The cost of this operation eventually drove the industry towards strategies of predominantly a two-year, single crop-cycle.

The Hawaiian Industry led the world in the adoption of technologies such as drip irrigation and crop ripening, and continuing research is being conducted on the monitoring and optimization of the management of these operations. While management of the crop agronomy has continued to improve, the basic mechanical operations associated with crop production (planting) along with the harvesting and delivery systems have changed relatively little for over five decades.

With the development of mechanical harvesting, and in particular chopper harvesting, in other sugar industries around the world, many attempts were made to introduce this technology to Hawaii. Australian manufacturers, such as the Toft Brothers, designed and manufactured a very large machine in an attempt to mechanically harvest the two-year crops. (See Figure 3-3.) The mass of the material associated with the two-year cropping system, and more importantly the presentation of the material resulting from the recumbent nature of the varieties developed under this cropping system, defeated all such attempts.

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14 Kerr, Bill and Ken Blyth. “They’re All Half Crazy: 100 Years of Mechanical Cane Harvesting” (1993) Published by Canegrowers. ISBN 0959885234 / 9780959885231
The Hawaiian Industry has traditionally been well supported by research and development (“R&D”), particularly in the traditional areas of agronomy and plant breeding. The uniqueness of the Hawaiian crop production system means that plant breeding strategies have reflected the different requirements of the crop under these growing conditions and harvesting methods. Emphasis was placed on characteristics which suited that farming system, including high biomass yields to maximize sucrose recovery rather than the more common strategy directed towards high sucrose content and more moderate biomass yields. (This is discussed further in Activity 2.) Similarly, R&D in the area of crop agronomy has primarily related to the specifics of the Hawaiian crop production systems.

Despite high cane yields at harvest and price support arrangements that have traditionally resulted in the price paid for sugar significantly above “world price”\textsuperscript{15}, the Hawaiian Industry has encountered problems. The lower sucrose recovery efficiency (relative to many other sugar industries around the world) and high input costs have placed the Hawaiian Industry under significant financial pressure. This has resulted in dramatic downsizing of the Hawaiian Industry over recent decades, with production declining from over 1 million tons per year to less than 200,000 tons.

\textsuperscript{15} “World price” as indicated by the New York raw sugar trading price.
3.3 Crop Option #1: Two-year Sugarcane, Burned for Harvest

The harvesting system essentially defines sugarcane production systems. The HC&S plantation follows the strategies developed by the Hawaiian Industry, and utilizes a nominal two-year crop-cycle, with pre-harvest burning under normal operating conditions.

Although the Industry initially utilized a crop production program that incorporated one or more ratoon-cycles, productivity and associated cost pressures have forced a move to a greater proportion of the crop being a single-crop from each replant. Available information is that over 80% of the crop at HC&S is now plant-crop only, with the seedcane nurseries comprising a significant proportion of the area which is ratooned. The crop is grown as a continuous monoculture with a short break for the mechanical operations associated with the crop replant program.

As a precursor to an analysis of alternative production systems available to HC&S, this section describes and current HC&S practices, which may be categorized into the following four general processes:

1) Field Preparation
2) Crop Establishment and Irrigation
3) Crop Maintenance
4) Harvesting and Sucrose Recovery

All the above processes have been developed to optimize/dovetail with the harvesting strategy which was co-developed as a response to labor availability and cost issues.

3.3.1 Field Preparation

3.3.1.1 Field Preparation Process

After harvest, HC&S’s land preparation process begins. Discussion with field staff indicates that the process can generally be described as follows.

1) The fields are ripped with a heavy ripper to a depth of approximately 24 inches in an attempt to break the compaction associated with the cane transport operation.

2) Some field leveling is undertaken to repair the surface profile after the harvesting operation, and a pass with heavy offset discs (36-inch disc diameter) is made to “break down” large clods that were formed by the ripping operation.
3) The entire field is then cross-ripped.

4) The field is then disced again with heavy disc harrows to “break down” clods. This is followed by a pass with lighter disc harrows to create appropriate soil tilth.

5) Ripping of the planting “lines” is undertaken with a lighter ripper mounted on a tractor fitted with Global Positioning System (“GPS”) “autosteer” guidance.

6) Repair work, as appropriate, is undertaken on the irrigation infrastructure prior to the planting operation.

The typical time between harvest and replanting is reported as approximately one month. This indicates a highly resourced, but very aggressive land preparation program. Figure 3-4 illustrates equipment used for the heavy ripping operation.

![Figure 3-4: Heavy ripper unit used for tillage operations](Photo credit: C.P. Norris)

By international standards, the energy associated with these crop replacement tillage operations can be argued to be very high when compared with a normal “plow-out and replant” operations for sugarcane in other sugarcane industries around the world. This is due to:
• The depth and aggressive nature of the tillage operations required to mitigate the impact of soil compaction from the very heavy cane haulage equipment

• The short replant cycle relative to the more typical four- to ten-year cycle for sugarcane replanting

### 3.3.1.2 Field Preparation Costs

As noted earlier, field preparation processes can be summarized as:

• Ripping and cross-ripping with heavy rippers drawn by a 300 hp class tracklayer tractor

• Discing and cross-discing with a large four-wheel drive articulated tractor and heavy discs

• Ripping of the planting lines with a medium-size four-wheel drive tractor and rippers

• Minor works, including rock removal as necessary

These operations were undertaken on the area harvested, less the area not replanted, i.e., ratooned, which was typically approaching 20%. The cost of the components of the tillage program is derived from two sources:

• Information on land preparation costs provided by HC&S, with an allowance for cost escalation

• Analysis of costs at a range of operations in African and South America with which lead researcher Chris Norris has been involved

The costs derived from this information, is presented in Table 3-1.

<table>
<thead>
<tr>
<th>Operation</th>
<th>$/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ripping</td>
<td>$ 67</td>
</tr>
<tr>
<td>Cross-ripping</td>
<td>$ 61</td>
</tr>
<tr>
<td>1st heavy discing</td>
<td>$ 60</td>
</tr>
<tr>
<td>2nd discing</td>
<td>$ 56</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$ 244</strong></td>
</tr>
</tbody>
</table>
From Table 3-1, the total cost of land preparation operations will be approximately $244/acre. This cost does not include costs such as drip irrigation, fertigation, herbicides or ripeners, or other associated costs.

### 3.3.2 Crop Establishment and Irrigation

#### 3.3.2.1 Planting the Crop

The HC&S planting operation involves approximately 16,000 acres per year, with a seedcane nursery area of approximately 1,630 acre, or approximately 10% of the crop area harvested. The planting process consists of a sequence of operations which have been selected to minimize the cost of the replant process. Given the relative frequency of replanting and the scale of the annual operation, cost management is very important. The ratio of approximately one acre of seedcane nursery to ten acres of crop area to be planted is typical of a number of industries worldwide, but well below the potential offered by some emerging planting technologies. The planting process can generally be described as follows.

Seedcane is mechanically harvested at approximately eight to nine months of age, and again as a ratoon at a similar age. “Claas 3000” 16 billet harvesters, which have the capability of harvesting a dual-row crop configuration, are used. (See Figure 3-5.) The billet length produced by these machines is nominally 12 inches, in erect cane. Because the billeting drum is the first component in the feed of the material after basecutting, factors which impact on the feed of cane into the machine affect billet length and billet length variability. Lodging of the cane crop therefore reduces billet length and increases the variability of billet length. Fuelling 17 also notes that with the Claas-type harvesters, as the degree of lodging increases, the quality of the billet decreases on these machines, although this relationship applies to some extent to all machine types. The billet length observed at

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16 These machines are no longer commercially available.

the time of a visit to HC&S was variable and ranged between 6 and 12 inches, which is consistent with expectations of the machine under the given conditions. (See Figure 3-6.) The average number of nodes per billet can be expected to be between two and three nodes, depending on the inter-node spacing of the cane being harvested.

1) The seedcane is directly loaded into mesh-walled crates (seed bins) that are individually transported beside the harvester by a wheeled loader. The crates have a nominal volume of approximately 128 ft³, and an estimated capacity of approximately 1.2 to 1.4 tons depending on the characteristics of the product. (Relevant characteristics of the product include billet length and trash levels. However, factors such as billet diameter also affect load density.) The loader stacks the crates in the field for subsequent loading onto truck/trailer units.

2) Truck/trailer units transport the seedcane billets to a hot water treatment (“HWT”) facility. At the HWT facility, the seedcane was traditionally dipped into 125 °F (51 ºC) water for 30 minutes (for smut control) and stimulation of germination and then into a cold water fungicide solution for one minute to control potential fungal rots. Some changes to this strategy have been introduced in recent times. Currently, the cane remains in the mesh-walled crates for the operation, and the crates are transported to the field edge in truck/trailer units and unloaded.

In the field, a wheeled loader is used to tip the seed bins into the hoppers mounted along the sides of the billet planters. The planters are self-propelled units developed for the Hawaiian Industry. HC&S operates five planters; three with tracked chassis and two on wheeled chassis. Several of the planters are now fitted with GPS “autosteer” guidance.
3) The planters simultaneously:

- Place two rows of drip tape at 9-foot centers, the standard configuration used by the Hawaiian Industry
- Open twin furrows 18 inches on either side of the drip tape (i.e., with three feet between the two furrows) for the seedcane billets
- Dispense the seedcane billets into the furrows at a planting rate of approximately 3 tons per acre
- Cover the billets with soil

Two views of a planter are shown in Figure 3-7 and Figure 3-8.

4) The billet metering system is of conventional design for billet planters and incorporates a single-stage belt with perpendicular billet metering slats and a “pusher” to move the billets along the hopper to contact the metering belt. While this configuration is robust and reliable, it provides relatively poor spatial accuracy for the billets in the seedcane furrows. This is characterized by “gluts” and “gaps” in the line of distributed billets. Further deterioration of spatial accuracy occurs as the furrow openers and seed delivery chutes respond to rocky field conditions. As partial compensation for these effects, planting rates used with this type of planter are higher than the planting rate required with planting systems that achieve better control over billet spacing. Despite this increased planting rate, the poor distribution associated with billet planting inherently results in some reduction in yield potential (Robotham and Chapple\textsuperscript{18}). Robotham\textsuperscript{19} notes that based on results in replicated trials, billet planting can be anticipated to result in a yield depression of approximately 5 to 10% relative to “optimum billet spacing”. Gaps in the emerged plant stand can also result in increased problems with weeds due to the time taken for the crop to achieve full canopy cover.

5) To mitigate the problem with gaps in the emerged plant stand, until recently, workers at HC&S followed the planters to redistribute billets that had been deposited in the “gluts” into the “gaps” before a separate mechanical covering


\textsuperscript{19} Robotham personal communication based on a Report on the Australian Government’s Sugar Research Development Corporation (“SRDC”) Project BS 165.
operation was undertaken. To reduce costs, this operation has been discontinued and the covering of the furrows is now done by the planter.

![Photo credit: C.P. Norris](image1)

Figure 3-7: Front view of planter showing overall layout

![Photo credit: C.P. Norris](image2)

Figure 3-8: Planter showing billet delivery chutes and furrow covering assemblies

### 3.3.2.2 Ratoon-Crop Establishment

While most of the fields are replanted after each harvest, approximately 20% of the harvested area is ratooned after each harvest. The sequence of this operation is as follows.

1) After harvest, areas of compacted soil (e.g., tracks left by haulage equipment) are ripped with a heavy duty ripper behind a high, large (300 hp class) tracklayer-type tractor.

2) After the crop regrowth (ratoons) begin to emerge (i.e., shoots are visible), a new drip line is re-injected and seedcane is inserted into visible gaps by a single-bed (dual-row) replanting unit. This is a smaller unit than the two-bed units used for the main planting operation.

As a result of the faster crop establishment of ratoon-crops and the faster canopy cover, less weed control is typically required for ratoon-crops.

### 3.3.2.3 Irrigation

Target water application by both irrigation and rainfall is quoted as approximately 72 inches per year (1,800 mm/yr). Rainfall varies significantly across the plantation, and consequently irrigation demand also varies. The availability of sufficient water for irrigation
can be an issue. “Water deficit” is identified as the most significant factor affecting yield potential.  

Irrigation is exclusively by drip irrigation. The design run-length is typically a maximum of 600 feet (according to HC&S Field maps), which then dictates field layout because of the positioning of water supply mains and manifolds. Sub-mains supply above ground distribution lines which feed the drip lines. The average run-length of drip tape over the farm is less than 600 feet, because of the significant percentage of shorter rows associated with irregular field shapes.

After the planting operation has been completed, the irrigation process is started. The irrigation system is reportedly run continuously for up to seven days to fully saturate the field. (See Figure 3-9.) After the initial irrigation, the water application is then scheduled based on evaporation potential in accordance with a water balance model developed at HC&S. An overview of the emerged crop configuration is illustrated in Figure 3-10. In the fields observed, gaps in the plant stand were consistent with expectations given typical planting conditions."
3.3.2.4 Cost of Planting the Crop

The cost of the mechanical operations involved with planting the crop includes the cost of harvesting the plant cane, post-harvest treatment and transport, and the cost of the planting operation. It does not include the cost of drip irrigation tape, fertilizer, or other associated costs.

Based on information from HC&S, the cost of the seedcane supply and planting operations, with an allowance for cost escalations, is assumed to be approximately $600 per acre. An estimate of the combined costs of land preparation and planting are as shown in Table 3-2 below.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost/Acre</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Preparation</td>
<td>$244</td>
<td>$3,989,000</td>
</tr>
<tr>
<td>Planting</td>
<td>$600</td>
<td>$9,800,000</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$844</strong></td>
<td><strong>$13,799,000</strong></td>
</tr>
</tbody>
</table>

The annual cost of land preparation and the planting operation is approximately $13.8 million.

3.3.3 Crop Maintenance

Crop maintenance after planting is covered in detail in a number of reputable publications (e.g. Santo et al.\(^{21}\)) that discuss the sugarcane cropping system in Hawaii. The primary operations include fertilizer application and weed control.

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3.3.3.1 Fertilizer Application

During the crop-growth cycle, the field is fertilized via the drip irrigation system, typically on a monthly cycle. There are large differences in the fertilization program based on soil analysis and water source (aquifer or mountain water), with application rates optimized on the basis of soil and leaf analysis. The “average” total annual fertilizer application is reported as:

- 200 lb/acre of nitrogen (“N”)
- 200 lb/acre of potassium (“K”)
- 50-250 lb/acre of phosphorus (“P”)

3.3.3.2 Weed Control

Weed control is achieved entirely by herbicides, with canopy closure of the crop occurring in as little as eight weeks in the summer months and somewhat longer in the cooler and windier months.

A two-year crop-cycle is claimed to offer significant weed control advantage over an annually-harvested burnt-cane crop production system. However, the long crop-cycle can result in difficulty in accessing weed infestation, which can be problematic. The primary weeds are reported to be vines and large grasses. Santo et al.\(^22\) notes “Guineagrass stools with diameters up to 3 ft may require the use of a backhoe because normal tillage and repeated application of glyphosate are ineffective”. Volunteer sugarcane emerging over the drip lines is apparently a serious problem requiring effective control to prevent pinching of the tubes.

3.3.3.3 Pesticide Application

While sugarcane in Hawaii is subject to some above-ground and below-ground insect pests, plant parasites, and some mammalian pests, the levels of infestation are generally low or very low and typically do not warrant control of any type. Therefore pesticides are not normally applied to a Hawaii sugarcane crop, except for the pre-emptive treatment of seedcane for control of smut, pineapple disease and ratoon stunting. Rat bait is applied to fields where infestation levels indicate control is necessary.

3.3.4 Harvesting and Sucrose Recovery

Key issues related to a harvesting system include:

- The direct cost of the harvesting operation, including the transfer of biomass to the factory
- Sucrose losses directly associated with the harvest and transport operation, and the impact of the presentation of the product at the factory on factory sucrose recovery
- The impact of the harvesting operation on the short and longer term sustainability of the crop and crop production system

3.3.4.1 Harvesting

As stated earlier, the harvesting system used by any sugarcane industry defines that industry and impacts on every other facet of the crop production system. The Hawaiian Industry is no exception. For this reason, it is appropriate to relate the “time line” of the crop-cycle around the harvesting operation. The harvesting practices undertaken at the HC&S plantation can be summarized as follows.

1) After maturation by irrigation management and aerial application of ripeners, most of the cane is “burned” immediately prior to harvest. This operation removes trash and leaves that are sufficiently dry to desiccate and burn. Due to a number of environmental and “good neighbor” constraints on burning, a small but increasing proportion of cane is harvested without being burned.

2) The crop is pushed into large windrows by “D8” tracklayer tractors (300 hp class) fitted with push rakes. (See Figure 3-11.) The rakes are designed (optimized) for the task of detaching the cane stalk and pushing it into windrows while minimizing soil inclusion.

3) Commercial high capacity excavators fitted with four jaw-grabs (with a capacity of approximately four tons) load the windrowed cane into large heavy-duty cane transport units. (See Figure 3-12.) Front-mounted rakes fitted to smaller wheeled loaders then “clean-up” cane which has been dropped, and move it to a nearby windrow for subsequent loading.
4) The cane transport units travel into the field and are direct loaded. The number of units utilized depends on the length of haul from the harvesting fronts to the mill. The number of vehicles in use therefore varies on a daily basis, normally ranging from 9 to 13 vehicles. The designs of these vehicles which haul the cane to the factory consist of a space frame trailer with chain slings, hauled by industrial tractor units. The nominal capacity of the trailers is estimated at approximately 8,500 ft³ (including an over-height load peak), providing a payload typically in excess of 65 tons of product, at an assumed conservative gross product density of 15 lb/ft³. The load density is affected by cane characteristics and loading strategies, and densities in excess of 15 lb/ft³ are considered probable. The trailers have a single axle fitted with industrial type tires in “singles” configuration at the rear and are supported on a hitch above the rear axle of the tractor unit.

5) Cane transport units operate entirely in-field and on private roads, because of both “over-size” considerations and “over-weight” considerations related to possible damage to public roads.

6) At the mill, the cane is discharged via a “spiller-bar” arrangement similar to designs widely used for wholestalk cane unloading systems around the world. (See Figure 3-13 and Figure 3-14.) Before the cane progresses to the shredder, the delivered product is passed through a cane cleaning (washing) system. This system removes rocks and soil which has been entrapped in the cane and bought to the mill during the harvesting operation.
The system operates with a minimal labor requirement. This harvesting method allows cane to be harvested from a wide-range of terrains and from rocky conditions. It also minimizes wet weather downtime. However, under rocky field conditions, the mass of rock carried into the mill with the cane can be anticipated to significantly increase. If pre-harvest burning is not possible, trash and soil levels in the delivered product will be significantly higher than the levels normally encountered with burned cane.

The current harvesting system used at HC&S demonstrably achieves a low cost per ton of biomass harvested and transported to the factory facility. Significant amounts of other material, predominantly soil and rocks of varying size (but also including drip tape) are entrapped in the load and also transported to the mill. A mill-based cane washing facility removes most of this material, resulting in a visually soil free product being forwarded to the shredder and milling train. This overall strategy is apparently successful in minimizing issues associated with rocks and soil in the cane supplied to the milling operation, and the associated issues of increased sugar ash levels, high levels of filter mud production, equipment damage and wear, etc. Figure 3-15 shows cane during the washing process, and Figure 3-16 is of the receival truck for rocks and soil particles which settle rapidly in the flotation hopper. The remaining soil, along with organic material is conveyed from the cleaner in the waste water flow.

Against these benefits relating to harvesting costs and the capacity of the system to harvest almost any crop, there are issues related to the following:

- High field costs predominantly associated with the single-harvest crop-cycle resulting from this crop production and harvesting strategy
• High losses of sucrose associated with the current harvesting system, and more significantly the cane washing system

![Figure 3-15: Cane during the washing process](Photo credit: C.P. Norris)

![Figure 3-16: Reject product being collected for disposal](Photo credit: C.P. Norris)

• The harvesting system is totally non-selective

Consequently, all material not removed in the pre-harvest burn are forwarded to the mill. This includes green leaf, dry leaf, and tops (stalk growing point and associated leaf sheath).

• The cane washing system currently has no facility to reduce levels of leaf material or tops in the delivered cane

When unburned cane is being milled, this material can be anticipated to reduce mill extraction and the milling rate (Kent\textsuperscript{24}), and sucrose recoveries (Kent\textsuperscript{25}, Moller\textsuperscript{26}).

\textsuperscript{23} A high proportion of the soil and organic material is conveyed away in waste water streams to settling ponds.


3.3.4.2 Benchmarking HC&S Harvesting Cost

HC&S’s harvesting cost includes the labor, capital, and operating costs associated with its component operations. The cost breakdown associated with each of the individual components of the harvesting process is not easily determined from available data. For the purposes of comparative analysis with alternative harvesting strategies, estimates for the different components of the harvesting process are derived in this section.

Key components of the harvesting process include the following.

1) **Pre-harvest burn operation:** Undertaken by a team of workers with supervision.

2) **Push-raking and windrowing:** “D8” tracklayer tractors (300 hp class) are utilized in the push-raking/windrowing operation; typically with two units used at each harvesting front. Although actual engine hours per year was not reviewed, it is anticipated that the annual utilization of these machines will be high. Field efficiency (which relates to the percentage of engine hours that the machine is engaged in useful work) is also likely to be high if the reversing component of the windrowing operation\(^\text{27}\) is considered part of the active work cycle. The time spent actually pushing will be approximately half this number.

3) **Loading:** The loading operation is undertaken by large hydraulic excavators fitted with four jaw-grabs. Since these are manufactured as industrial units, and designed to handle relatively high production volumes, they can be anticipated to have lower capital and operating costs than more typical cane loaders of similar capacity. This is because the lower demand for cane loaders results in limited R&D effort during design (which tends to raise a unit’s operating costs), and production in smaller manufacturing batch sizes (which leads to a higher capital cost). The hourly cost of machine operation can therefore be anticipated to be lower than that of a cane loader.

4) **“Cleanup” operation:** Typically called “gleaning” or kolili in Hawaii, this is undertaken by four-wheeled loaders, and would be of relatively low cost.

5) **Cane haulage:** This is undertaken with high volume haulage units of rugged utilitarian design.

The actual allocation of the exact cost of the current harvesting operation is relatively unimportant in “big picture” analyses, providing realistic comparative analysis of the cost of harvesting.

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\(^{27}\) The “reversing component of the windrowing operation” is the amount of time the machine is in reverse.
different harvesting options can be assessed. Table 3-3 develops indicative cost for the different components of the harvesting process based on the personal experience of lead researcher Chris Norris, with allowance for labor costs in Hawaii.

<table>
<thead>
<tr>
<th>Table 3-3: Indicative cost of harvesting operation for burned cane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation</strong></td>
</tr>
<tr>
<td>Pre-harvest Burn</td>
</tr>
<tr>
<td>Windrowing with D8 Tractors</td>
</tr>
<tr>
<td>Loading with Hydraulic grab loader</td>
</tr>
<tr>
<td>Cleanup after loading</td>
</tr>
<tr>
<td>Cane Transport</td>
</tr>
<tr>
<td>Total cost per ton product delivered at mill</td>
</tr>
</tbody>
</table>

This dataset is based on Mr. Norris’ experience at a large number of projects worldwide. “Benchmark” costs can be approximated at $6.60 per ton for the harvesting and transport operation, including an allowance for machine replacement. This harvest cost is based on the gross product mass delivered to the sugar mill receival facility.

While a derived number such as this has potential for significant “component” error, the primary goal of this exercise is to provide a realistic “relative cost” benchmark against which the harvesting operation associated with other strategies may be compared. The comparative harvesting cost per acre can then be determined by the cost ($/t) for each system and the tonnage loaded and transported from the field to the mill complex. Harvesting costs, per se, are a relatively minor component in overall system economics.

### 3.3.4.3 Benchmarking HC&S Recovered Sugar Yield and Derived Crop Yields

As previously noted, the Hawaiian Industry is well known for its high productivity and the subsequently high tonnages associated with a two-year harvest cycle. The Industry
has also been at the forefront of developments such as the optimization of irrigation management, including the widespread adoption of drip irrigation. The Industry was an early adopter of strategies such as irrigation management and the use of ripeners to maximize potential sucrose recovery. Both are now routine tools in many sugar industries throughout the world.

To appropriately assess different crop production and associated harvesting systems, actual crop yields for HC&S must be derived as no significant data is available on the actual tons of clean cane delivered to the mill from the field. The derivation of cane yield then allows an assessment of alternative cropping and harvesting strategies, and the likely effect these strategies would have on sucrose recovery.

HC&S sugar production between its 1996 season and its 2008 season is shown in Figure 3-17. Discounting the years after 2005 where issues such as irrigation availability and crop nutrition impacted on yield, the sucrose recovered per acre harvested on a 10-year moving average is 12.36 tons sugar per acre (“t/ac”) harvested as “two-year” cane. The average HC&S yield for nine-years (1996 to 2004) is 12.44 t/ac harvested.

![Figure 3-17: Sugar production at HC&S 1996-2008](image)

The determination of the relative performance of a cropping system is compounded by several considerations.

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28 Source: HC&S
• Many industries assess crop performance on monthly productivity between the time of planting (or previous harvest in the case of ratoons) and the harvest; i.e., the actual crop age in months at harvest is determined as a strategy to compensate for typically different plant-crop and ratoon-crop age at harvest.

• The Hawaiian Industry has generally referred to its crop as “two-year cane”, i.e., nominally the age at harvest is two years. However average age at harvest will typically be 24 months less the time required for the replant operation. The time available for crop growth will typically range between 22 and 23.5 months, with 23 months assumed as “average” for the purpose of analysis.

• The issue of productivity is further compounded by the fact that crop biomass accumulation with time actually follows a sigmoid relationship, rather than a linear relationship.

Overall cropping system productivity is best assessed on the basis of average productivity (cane stalk and sucrose) per year, with the period of non-crop being considered a part of the cropping system. Conversely, crop growth rates can be argued to be better assessed on the basis of productivity per month.

Yield data presented in Activity 2 indicates that the average yield over 27 years is 0.522 t/acre/month (based on 24 months “nominal” crop age at harvest), with the 2011 harvest again achieving this benchmark. HC&S staff believes that this long-term yield can at least be maintained and probably be exceeded by maximizing utilization of water potentially available to the plantation.

For the purposes of this study, a “delivered sugar yield” of 12.5 t/acre harvested\(^{29}\), on a two-year crop-cycle, will be used as the baseline. This equates to:

• A cropping system productivity of 6.25 t/acre/year

or

• A crop sugar productivity of 0.54 t/acre/month\(^{30}\) of crop growth

This yield target is marginally greater than the 27-year “averaged” yield, and reflects targets which are considered by HC&S staff to be realistic.

Data presented in Activity 2 indicates that the long-term average productivity of the different sections of the HC&S plantation ranged between 11.2 and 12.75 t/acre at harvest. Discussion with staff indicates that water availability tends to override all other factors, with

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\(^{29}\) Calculated as 24 months x 0.522 t/acre/month

\(^{30}\) Calculated as 12.5 t/acre per 23 months available for crop growth.
yield believed to be controlled by water availability rather than other agronomic and field limitations.

These recovered sugar yields confirm the status of Hawaii as a high yielding sugar production region. However, high yields are also encountered in other parts of the world and a degree of “cross referencing” is worthwhile to develop an understanding of the issues. Lead researcher Chris Norris has significant experience in other high yielding sugarcane growing areas. Two areas of note are the Burdekin area in Australia (approximately 19°30’ S, 147° E) and Swaziland (approximately 26°07’ S, 31° E) in Southern Africa.

- Wegner\textsuperscript{31} notes that the average sugar production from the Burdekin sugarcane production area in Australia (production in excess of 7 million tons cane per year) was 5.8 t/acre/year for the period 1980 to 1997, averaged over the total area registered with the sugar mills for growing sugarcane. The crop is fully machine harvested and crop age is typically slightly less than 12 months, because of the predominance of the strategy of “plow-out and replant” at the end of the ratoon-cycle. The sugar production per harvested acre per month can therefore be anticipated to be approximately 6 t/acre/year.

- The sugar industry in Swaziland produces approximately 5 million tons of cane per year, with approximately one-third of the area farmed by small growers and the remainder by millers and large growers. The small growers achieve significantly lower yields than the estate-farmed land.
  
  o Tabankulu Estate\textsuperscript{32} (26°07’51.47” S; 31°55’48.18” E altitude 700 feet) typically produces 68,200 tons of sugar annually off 9,270 acres; an average of 7.4 t\textsubscript{c} farmed acre/year. It uses predominantly overhead irrigation systems. The farmed area includes the area cropped for seedcane, as well as land out of production for fallow, which can be up to six months.

  o Royal Swaziland Sugar Corporation (“RSSC”) adjoins Tabankulu and has over 22,000 acres under drip irrigation. The average production from this area of the estate over an extended period has ranged between 6.9 and 8.1 t/acre/year\textsuperscript{33}. The crop-cycle is typically plant-crop plus eight to nine ratoons with annual harvest. The yield decline over the crop-cycle is in


\textsuperscript{32} http://www.huletts.co.za/ops/swaziland.asp (Accessed: 26 Jan 2012)

the order of 30%. (This estimate is based on the personal observations of lead researcher Chris Norris). Productivity in the plant-crop is in the order of 8.1 to 9.5 t/acre/year. Water availability is considered a significant issue on this Estate, with yields often limited by water deficit, because of limits to the supply of water to the Estate.

The Australian industry is fully machine harvested, whereas the Tabankulu Estate is fully hand-cut. RSSC typically practices a combination of machine harvesting and hand-cutting. All figures are based on sucrose recovered after the milling operation.

As previously noted, the HC&S average sugar production is approximately 6.25 t/acre/year. This is higher than the fully machine harvested Burdekin region of Australia, but lower than the African estates. As discussed in the following sections of this report, sucrose recoveries associated with the harvest and cane washing system very adversely impact on sugar recoveries in Hawaii, relative to other high producing countries. A reduction in these losses would result in a significant increase in recovered sugar yield.

3.3.4.4 Sugar Recovery for Current Harvest and Milling System

The potentially recoverable sugar in the crop immediately prior to the pre-harvest burn represents the maximum attainable sucrose recovery. Virtually every operation after that point results in some reduction in the potentially recoverable sugar.

Losses of sucrose, either by gross material losses or by deterioration, are inevitable when harvesting and processing a product such as sugarcane. Examples of losses in other industries can be used as appropriate benchmarks.

- Gomez et al.\(^{34}\) in Argentina conducted a series of 32 paired trials investigating, for burned and unburned cane, the sequential loss of sugar which occurs between the field and the mill. The trial was undertaken utilizing late-model chopper harvesters as the only harvesting method. The results of the trials indicated that with green cane harvesting, total sugar recovery averaged 84.2% of pre-harvest recoverable sucrose in the cane stalk. With burnt-cane harvesting, the recovery averaged 83.9%. This equates to a total loss of 16.1% of pre-harvest available sugar in the burned cane trial and 15.8% in the green

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cane harvesting trial. The most significant loss component in both systems was observed to be the billeting loss in the harvester, which was derived to be approximately 5% for both green cane harvesting and burnt-cane harvesting.

Other significant losses included the loss associated with burning the crop (reduction in recoverable sugar associated with the burn and subsequent accelerated deterioration), which averaged 4.7% across these trials. In an earlier series of trials under cool conditions, Gomez noted that average losses were somewhat lower at 2.5%. In green cane harvesting, the loss associated with trash extraction averaged 3.4%. It should be noted that the management at the mill aggressively implement a policy of very low harvester extractor speeds to minimize cane loss from the extractor, even at the expense of reduced milling recoveries.

- Burleigh et al.\textsuperscript{35} conducted a series of trials in Sudan to determine the relative cane recoveries and the recoverable sucrose in delivered burnt cane from both manual cutters (wholestalk, machine loaded) and chopper harvested cane. The data indicated that the average recoverable sucrose in the cane in the field pre-harvest was 6.33 t/acre (14.21 t/ha). Hand-cutting resulted in the potential recovery of 5.84 t/acre (13.1 t/ha), and chopper harvesting resulted in potential recovery of 4.49 t/acre (10.07 t/ha). Losses therefore ranging from 8.7% for hand-cut cane to 25.5% for chopper harvested cane. It should be noted that the machine harvesting losses reported in these trials is higher than would be anticipated with a modern, well-managed chopper harvesting operation.
  
  - Significant changes in chopper harvester design, particularly the design of the billeting system, have occurred since these trials were conducted. This would reduce losses.
  
  - Ambient temperatures typically encountered in Sudan results in rapid deterioration of cane after pre-harvest burning. These losses are dramatically reduced in green cane.

The harvesting system used in Hawaii is unique, and research has been undertaken to assess the losses in this system. End Table 3-1\textsuperscript{36} provides datasets from a number of trials


\textsuperscript{36} End Table 3-1 is located at the end of the report, on page 193.
conducted between 1978 and 1981 by the Hawaiian Sugar Planters’ Association (“HSPA”) to quantify sugar losses within the Hawaiian Industry.\textsuperscript{37} Available information is that, the baseline data was taken from the freshly burned crop. Sampling and measurements were then taken at key points in the process, to allow sucrose “flow” and losses to be determined. This data provides an excellent snapshot of the Industry at a stage when it was much larger than it is now. The datasets also provide a good baseline for the assessment of the performance of the Hawaiian Industry harvesting system and yields generally.

To fully assess the losses associated with harvesting sugarcane, all losses including the losses associated with pre-harvest burning, must also be accounted for. As indicated above, Gomez\textsuperscript{38} measured losses associated with pre-harvest burning. Results (from two large-scale series of trials) averaged 2.5% and 4.7%, respectively, of the recoverable sucrose in the crop, pre-firing. The 4.7% average was derived from a series of 32 trials. He observed that the observed loss value was a function of a number of factors, including the “heat” of the fire and cane condition at time of burning.

Figure 3-18 graphically presents the dataset from End Table 3-1, including a very conservatively assumed 3% for the loss associated with the burning process. Figure 3-18 also includes an “average” dataset based on the values in the full dataset. This is the last column in Figure 3-18.

\textsuperscript{37} Personal communication with retired HSPA executive Robert V. Osgood, Ph.D. between June 2010 and October 2011 regarding reports by the HSPA Plantation Agricultural and Processing Practices (“PAPP”) committee. Dr. Osgood is the lead researcher for the second of this six-part Biofuels Assessment; Activity 2 – Crop Assessment.

Figure 3-18: Breakdown of the initial sucrose levels in the field into loss streams and final recovery

Ignoring the unmeasured losses associated with pre-harvest burning, this dataset indicates the following.

- Field losses ranged from 0.2 t/acre (one case only with the next lowest being 0.8 t/acre) to 3.4 t/acre, and averaged 1.7 t/acre.

- Cleaning (cane laundry) losses ranged from 1.7 to 6.6 t/acre, and averaged 4.08 t/acre.

- Milling losses (including POL\textsuperscript{40} losses in bagasse), losses to filter mud, and undetermined losses ranged from 0.3 to 1.66 t/acre, and averaged 0.86 t/acre.

\textsuperscript{39} Personal communication with retired HSPA executive Robert V. Osgood, Ph.D. between June 2010 and October 2011 regarding reports by the HSPA Plantation Agricultural and Processing Practices (“PAPP”) committee. Dr. Osgood is the lead researcher for the second of this six-part Biofuels Assessment; Activity 2 – Crop Assessment.
Losses to molasses ranged from 0.77 to 1.28 t/acre, and averaged 1.05 t/acre.

Figure 3-19 further develops this data and presents the sucrose recovery and individual losses as a percentage of the derived initial sucrose level in the pre-harvest crop.

Figure 3-19: Distribution of sucrose initially in the crop pre-harvest to various losses and final recovered sugar

Analysis of the data in Figure 3-18 and Figure 3-19 indicates that, in addition to the initial loss associated with burning (conservatively assumed at 3% or 0.53 t/acre in the averaged data), losses associated with other components of the harvest, transport, washing and milling processes were as follows.

40 “POL” is an estimate of sucrose based on optical measurement of positive light rotation substances in cane juice.

41 Personal communication with retired HSPA executive Robert V. Osgood, Ph.D. between June 2010 and October 2011 regarding reports by the HSPA Plantation Agricultural and Processing Practices (“PAPP”) committee. Dr. Osgood is the lead researcher for the second of this six-part Biofuels Assessment; Activity 2 – Crop Assessment.
Losses associated with harvesting ranged from approximately 1% to approaching 20%, with losses in over 60% of the fields between 7% and 14% and averaging approximately 9% of pre-harvest sucrose. This loss is assumed to be primarily attributable to material left in the field, with some contribution from sucrose loss associated with stalk damage during the windrowing and loading processes. The total reported field losses appear relatively high given the visibly moderate levels of material typically left on the surface in the field. However, losses of this magnitude are considered realistic, based on both the sucrose losses associated with cane stalk damage and the significant additional cane stalk cane which is not visible because it has been buried by the windrowing process.

Losses associated with the cane washing system ranged from 10 to 37% of the pre-harvest sucrose levels, with the majority of results indicating losses between 20 and 25%. The average of all datasets was approximately 22% of the pre-harvest sucrose. This was typically the greatest single source of losses in the sugar harvesting and recovery operation.

Discussions with HC&S staff indicated that other studies into this source of losses have been conducted in Hawaii. At least one of these studies was based on an analysis of the proportion of stalk-length damaged and the relative weight and sucrose recovery from both sound and damaged stalks. This trial protocol reportedly estimated average losses to be in the order of 27%, under the conditions of the trials.

Work by Birkett and Stein\(^\text{42}\) in Louisiana with both billeted (chopper harvested) and machine harvested wholstalk cane found that the most significant factor impacting on washing losses was the degree of damage to the stalk associated with the harvesting operation, rather than the billet length per se, although the number of exposed billet ends is still significant.

Rudimentary analysis of a sequence of 2011 photographs of cane stalk on conveyors immediately after the laundry at HC&S indicates very high levels of damaged stalk. In addition, the “average stalk length” of the product on the conveyor after the cane cleaning plant visually appears to be significantly shorter than the average stalk length of delivered cane. This implies significant additional cane stalk breakage. Therefore, sugar loss values of the magnitude reported appear reasonable, although the cane stalk typical mode of failure

(breaking and mode of breaking or buckling) will also impact on losses in this situation. An average value of 22%, as determined by the HSPA trials summarized on End Table 3-1, is assumed to be an appropriate and conservative baseline for cane laundry losses.

- Combined losses of sucrose to bagasse, filter mud, and undetermined losses averaged approximately 0.86 t/s/acre or approximately 5% of the initial pre-harvest sucrose levels. Realistically, sucrose milling losses must be determined relative to the product entering the milling train. On this basis, the combined losses of sucrose are approximately 7.4% of the sucrose entering the milling train, with the breakdown from the raw data as follows:
  
  o  Bagasse 5.3% of sucrose entering the milling train
  
  o  Filter mud 0.7 % of sucrose entering the milling train
  
  o  Undetermined losses 1.4% on the same basis as the bagasse and the filter mud

- Losses to molasses averaged 1.05 t/s/acre, and on the basis of sucrose entering the milling train, this equates to approximately 8.7%.

The combination of losses in the milling process averaged approximately 16.1% of the sucrose entering the milling train. These losses are consistent with losses observed in other industries. The South African industry is widely reputed as being an excellent performer with respect to sugar recovery efficiency in its sugar mills. Sugartech\(^43\) notes:

> “The data below are the industry average figures from South African factories as published in SASTA Proceedings. The figures given in the table and graph below are as a percentage of the sucrose entering the factory in cane. The losses in 1993 and 1994 were high as a result of the drought at that time. It is quite clear that the losses in bagasse and filter cake are almost constant, while the loss in molasses varies a lot. The undetermined loss is fairly stable from year to year.”

Table 3-4 is the table that was included in the Sugartech article.

<table>
<thead>
<tr>
<th></th>
<th>Bagasse</th>
<th>Filter Cake</th>
<th>Molasses</th>
<th>Undetermined</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>1988</td>
<td>2.37</td>
<td>0.27</td>
<td>9.64</td>
<td>1.96</td>
<td>14.24</td>
</tr>
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<td>9.26</td>
<td>1.85</td>
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<td>1990</td>
<td>2.33</td>
<td>0.26</td>
<td>8.76</td>
<td>1.98</td>
<td>13.33</td>
</tr>
<tr>
<td>1991</td>
<td>2.25</td>
<td>0.29</td>
<td>9.02</td>
<td>1.92</td>
<td>13.48</td>
</tr>
<tr>
<td>1992</td>
<td>2.05</td>
<td>0.27</td>
<td>8.86</td>
<td>1.76</td>
<td>12.94</td>
</tr>
<tr>
<td>1993</td>
<td>2.19</td>
<td>0.25</td>
<td>11.31</td>
<td>2.23</td>
<td>15.98</td>
</tr>
<tr>
<td>1994</td>
<td>2.25</td>
<td>0.25</td>
<td>12.07</td>
<td>2.29</td>
<td>16.86</td>
</tr>
<tr>
<td>1995</td>
<td>2.13</td>
<td>0.22</td>
<td>10.97</td>
<td>2.01</td>
<td>15.33</td>
</tr>
<tr>
<td>1996</td>
<td>2.31</td>
<td>0.22</td>
<td>11.37</td>
<td>2.15</td>
<td>16.05</td>
</tr>
<tr>
<td>1997</td>
<td>2.28</td>
<td>0.25</td>
<td>9.84</td>
<td>1.81</td>
<td>14.18</td>
</tr>
<tr>
<td>1998</td>
<td>2.26</td>
<td>0.24</td>
<td>9.40</td>
<td>2.00</td>
<td>13.90</td>
</tr>
<tr>
<td>1999</td>
<td>2.27</td>
<td>0.25</td>
<td>9.29</td>
<td>2.10</td>
<td>13.91</td>
</tr>
<tr>
<td>2000</td>
<td>2.07</td>
<td>0.19</td>
<td>9.25</td>
<td>1.99</td>
<td>13.50</td>
</tr>
<tr>
<td>2001</td>
<td>2.25</td>
<td>0.18</td>
<td>9.45</td>
<td>1.92</td>
<td>13.80</td>
</tr>
<tr>
<td>2002</td>
<td>2.04</td>
<td>0.18</td>
<td>8.62</td>
<td>1.87</td>
<td>12.71</td>
</tr>
<tr>
<td>2003</td>
<td>2.21</td>
<td>0.15</td>
<td>8.96</td>
<td>1.67</td>
<td>12.99</td>
</tr>
<tr>
<td>2004</td>
<td>2.13</td>
<td>0.17</td>
<td>9.48</td>
<td>1.95</td>
<td>13.73</td>
</tr>
<tr>
<td>2005</td>
<td>2.02</td>
<td>0.14</td>
<td>9.65</td>
<td>1.96</td>
<td>13.77</td>
</tr>
<tr>
<td>Average</td>
<td>2.21</td>
<td>0.23</td>
<td>9.73</td>
<td>1.97</td>
<td>14.14</td>
</tr>
</tbody>
</table>

The total milling losses at HC&S are therefore generally consistent with the losses recorded in South African factories, although bagasse losses are nominally higher and molasses losses are nominally lower than African averages.

The combination of all losses averages approximately 10.12 t/acre, or approximately 45% of the sucrose in the field prior to harvest. Of these losses, the milling losses are within typical parameters for “wholstalk” production systems, as are the losses attributable to pre-harvest burning.
It is important to note that the benchmark used in these (HSPA) trials is *total sucrose pre-harvest, (but post-burning)* rather than recoverable sucrose in the cane stalk pre-harvest. The total recovered sucrose in the trials includes sucrose in the molasses.

The “averaged” losses identified in the HSPA trials can be used to derive pre-harvest cane yields for the HC&S plantation based on annual sugar production.

### 3.3.5 Benchmarking Productivity at HC&S

Key considerations relating to sugarcane productivity are sucrose in the field prior to harvest, and tonnage of material harvested and delivered to the factory, and losses.

#### 3.3.5.1 Field Productivity

As noted above, in the absence of other appropriate data, sucrose productivity of crops at HC&S can best be determined by “reverse engineering”, and deriving field pre-harvest sucrose productivity from final recovered sugar and anticipated losses.

The analysis of losses presented in Figure 3-18 and Figure 3-19 indicates that average sucrose losses in the harvesting, washing, and milling operation are approximately 45%. Further analysis indicates that the two HC&S mills (Paia and Puunene) were close to this average in all classes of loss, except for the very low indicated field loses for the trial at Puunene. Field losses in the trial at Puunene were only 1%, while the average for the trial program was 9%, with most results between 7 and 14%. Field losses recorded in the trial at Paia were 9%.

For the purposes of benchmarking for further analysis, it is assumed that sucrose recovery is 55% of the sucrose in the field immediately prior to the commencement of the harvesting operation (i.e., the pre-harvest burn). Given a sugar recovery of 12.5 t/acre harvested, this then equates to:

- A sugar yield pre-harvest of 22.7 t/acre at harvest
  or
- A productivity of nominally 0.99 t/acre/month at the typical average crop length of 23 months.

#### 3.3.5.2 Cane Productivity: Mill

Information on the actual tonnage of cane crushed is limited, because loads from the field are not weighed. Instead, cane delivered to the factory is derived from the outputs from the milling train (juice weight and bagasse estimated weight), less additions (e.g., maceration water).
Product removed from the cane cleaning facility is not weighed. As a significant amount of cane product (juice, pith, etc.) is removed in solution with the discharge water, a full mass balance analysis would have to also take this into account. The information required to achieve such an analysis is not available.

Available data indicates annual productivity targets as follows:

- Net tonnage of cane delivered to milling rollers: 1.47 million tons, estimated
- Anticipated sugar production: 200,000 tons
- Fiber in bagasse (dry ash-free fiber): 231,000 tons, estimated

This then equates to:

- 13.6% recoverable sucrose in product entering the milling rollers
- 15.1% fiber in product entering the milling rollers

### 3.3.5.3 Cane Productivity: Pre-Harvest

A determination of the typical pre-harvest cane tonnage is achieved by an assessment of anticipated mass losses during the pre-harvest burn, harvest and transport, and the cane laundry. Broadly similar techniques and protocols were used by Berding et al.\textsuperscript{44} to determine the losses associated with chopper harvesting.

Based on the HSPA trials (PAPP Committee\textsuperscript{45} Report) on the magnitude of sucrose losses and the nature of the process, the mass loss associated with the process can be "derived". Table 3-5 presents a simplified assumption of total mass loss (physical loss of cane components, including fiber and juice) and the recoverable sucrose loss (e.g., leaching and loss of juice and juice rich pith material and deterioration) which occurs.

---


\textsuperscript{45} The HSPA Committee on Plantation Agricultural and Processing Practices (“PAPP Committee”) reviewed plantation practice in field and factory.
Table 3-5: Simplified estimate of mass and recoverable sucrose losses associated with cane harvest and pre-milling laundry processes

<table>
<thead>
<tr>
<th></th>
<th>Assumed Mass Loss</th>
<th>Assumed Additional Sucrose Loss (accelerated deterioration, leaching and sucrose rich pith mass loss)</th>
<th>Total Loss in Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-harvest Burn</td>
<td>0%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Harvest Loss</td>
<td>9%</td>
<td>0%</td>
<td>9%</td>
</tr>
<tr>
<td>Cane Cleaning Loss</td>
<td>6%</td>
<td>16%</td>
<td>22%</td>
</tr>
<tr>
<td>Loss prior to Milling Train (Cumulative)</td>
<td>16%</td>
<td>18%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Table 3-5 indicates a total recoverable sucrose loss of approximately 34% between pre-harvest burn and the delivery of the product to the milling train based on the HSPA trial results. This loss can be expected to be comprised of:

- Physical loss of product mass, such as direct harvesting losses and physical loss of product (often pith and short fiber product from damaged stalk) in the cane washing process
- Deterioration associated with the pre-harvest burn, and “kill to mill” delay
- Selective loss of sucrose through leaching and other losses of free juice and pith components (juice in pith matrix) during the cane cleaning process

For the purpose of analysis, the loss of mass between pre-harvest burn and the milling train is assumed to be approximately 16%, with the remainder of the 34% sucrose loss reported in the trials associated with a nominal reduction in sucrose concentration in the material delivered to the milling train through deterioration leaching and other processes. This effect occurs both because of a proportionally greater loss of juice and pith relative to rind fiber, and due to deterioration of the sugars in the stalk facilitated by stalk damage.

Using this analysis strategy, the mass of the cane in the field prior to harvest each year will be in the order of 1,750,000 tons.\textsuperscript{46} Based on a cropped area of 36,000 acres and

\textsuperscript{46} The anticipated amount of cane crushed is calculated by assuming the mass loss between “cane in the field” and cane crushed at the mill is 16%. 
an area of approximately 1,650 acres used annually for seedcane (discussions with HC&S staff), the annual harvested area is approximately 16,350 acres. The average crop yield pre-harvest will be approximately 107 tons per acre. This tonnage is at variance with the “nominal” cane delivery to the rollers anticipated by HC&S, but is believed to be an appropriate baseline for further analysis.

### 3.3.5.4 Harvesting Costs

Harvesting costs are determined by the total biomass delivered to the mill complex, and is assumed to be the mass of cane, along with green leaf and dry leaf remaining after the pre-harvest burn and harvesting operation. Analysis of components from modeling allows a determination of the total tonnage delivered to the industrial facility, and the subsequent cost of harvest and transport operations. The total tonnage is estimated as:

1. Total cane stalk tonnage plus mass associated with cane tops and leaf remaining after the harvest
2. Soil rock and other contaminants included in the product forwarded to the mill less
3. Losses in the field of cane stalk, tops and leaf

These values are determined on the basis of:

- Anticipated loss of mass of leaf components during the pre-harvest burn, and typical levels of mass loss associated with dehydration of leaf material which does not burn
- Cane, tops and leaf loss associated with the harvest windrow and load operation
- Expected levels of soil and other “extraneous matter” which is forwarded to the mill with the cane, based on typical cane loading operations with grab loaders, with an allowance for the increased inorganic material anticipated because of the windrowing and loading techniques

Spreadsheet modeling\(^\text{47}\) can be utilized to derive an assessment of the impact of changes to crop and harvesting parameters on sucrose and fiber recoveries\(^\text{48}\). This allows

\(^{47}\) The model used in this analysis was developed by lead researcher Chris Norris and is proprietary. It was not developed for the purposes of this project (i.e., the Biofuels
both fiber mass and recoverable sucrose to be easily assessed through all processes from pre-harvest to mill recoveries. It also facilitates a detailed assessment of different harvest and transport scenarios, and the impact on fiber and sucrose recoveries. For example, changing the assumed efficacy of the pre-harvest burn:

- Can be optioned to change the assumed sucrose loss associated with the burn
- Changes the loss of both fiber and moisture from leaf, green leaf and tops
- Assesses the impact of these parameters on transport densities
- Assesses the impact of cane quality and non-cane material on sucrose recovery

The spreadsheet modeling approach also allows the inclusion of harvesting parameters, including both losses and non-cane components, as well as an assessment of the impact of changing variables. The input of this model for the “base case” scenario is summarized in Table 3-6. The model uses internal databases of research data to assign values to fiber, POL and Brix (REFSOL\(^49\)) of the cane trash components. The model then sequentially analyses mass and sucrose flow through the processes from the field to the mill.

---

Assessment described in Section 3.1.1). Based on information provided in this report, similar spreadsheet models may be constructed to support other alternative biofuel production operations.


\(^{49}\) “REFSOL” is refractometer solids, the soluble ash and sugar percent in plants.
Table 3-6: Input data for "base case" analysis of cane harvest and milling processes

<table>
<thead>
<tr>
<th>Crop Characteristics</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-harvest</strong></td>
<td></td>
</tr>
<tr>
<td>Pre-harvest clean cane (stalk) yield</td>
<td>107 t/ac</td>
</tr>
<tr>
<td>Annual harvest push rake</td>
<td>16,350 ac</td>
</tr>
<tr>
<td><strong>Pre-Harvest</strong> cane juice POL in clean cane stalk</td>
<td>22.3%</td>
</tr>
<tr>
<td><strong>Pre-harvest</strong> juice REFSOL in clean cane stalk</td>
<td>24.7%</td>
</tr>
<tr>
<td>Pre-Harvest - Fiber % in clean cane stalk</td>
<td>13.7%</td>
</tr>
<tr>
<td>- % recoverable sugar</td>
<td>16.5%</td>
</tr>
<tr>
<td>Burning Loss (% recoverable sucrose)</td>
<td>3.0%</td>
</tr>
<tr>
<td>Tops (pre-harvest) - fresh weight</td>
<td>2.9 t/ac</td>
</tr>
<tr>
<td>- % of pre-harvest biomass</td>
<td>2.3%</td>
</tr>
<tr>
<td>Green Leaf (pre-harvest) - fresh weight</td>
<td>4.2 t/ac</td>
</tr>
<tr>
<td>- % of pre-harvest biomass</td>
<td>3.3%</td>
</tr>
<tr>
<td>Dry Leaf (pre-harvest) - fresh weight</td>
<td>12.8 t/ac</td>
</tr>
<tr>
<td>- % of pre-harvest biomass</td>
<td>10.1%</td>
</tr>
<tr>
<td>Total pre-harvest leaf and tops - weight</td>
<td>19.9 t/ac</td>
</tr>
<tr>
<td>- % total weight</td>
<td>16%</td>
</tr>
<tr>
<td>Total biomass in field before pre-harvest burn</td>
<td>126.9 t/ac</td>
</tr>
<tr>
<td></td>
<td>Fresh weight</td>
</tr>
<tr>
<td><strong>Push harvest</strong></td>
<td></td>
</tr>
<tr>
<td>Field losses (cane stalk)</td>
<td>9%</td>
</tr>
<tr>
<td>Rocks, Soil, other EM* in load - wt</td>
<td>6.4t/ac</td>
</tr>
<tr>
<td>- % total wt</td>
<td>6%</td>
</tr>
<tr>
<td>Field burn, windrowing and loading costs (burnt cane)</td>
<td>$3.30/t</td>
</tr>
<tr>
<td>Haulage Unit Volume</td>
<td>8,500 ft³</td>
</tr>
<tr>
<td>&quot;Round Trip&quot; - cost of transport unit</td>
<td>$215</td>
</tr>
<tr>
<td>- nominal payload</td>
<td>65t</td>
</tr>
<tr>
<td>- $/ton</td>
<td>$2.55/t</td>
</tr>
<tr>
<td><strong>Cane Laundry and Trash Separation</strong></td>
<td></td>
</tr>
<tr>
<td>Mass loss</td>
<td>6%</td>
</tr>
<tr>
<td>Additional sucrose loss in washing system</td>
<td>16%</td>
</tr>
<tr>
<td>Total sucrose loss associated with laundry/cleaning system</td>
<td>22%</td>
</tr>
<tr>
<td>Ownership &amp; operating cost [$ /t] product to mill</td>
<td>$2.55/t</td>
</tr>
<tr>
<td><strong>Mill Rate</strong></td>
<td></td>
</tr>
<tr>
<td>Mill Fiber Crushing rate</td>
<td>50.00t/hr</td>
</tr>
</tbody>
</table>

* extraneous matter ("EM")
The data entered in Table 3-6 is then utilized by the model to determine outputs. The model allows the selection of typical leaf fresh weight as a percentage of pre-harvest cane stalk weight, and utilizes internal databases to determine factors such as fiber percentage and moisture content. In the “base case” scenario of burnt-cane harvesting, the model assumes that in cane which has been aggressively ripened prior to the pre-harvest burn:

- 90% of the dry leaf fiber is removed by burning
- 40% of the “green” leaf fiber is burned, (40% reduction in fiber), with an additional degree of desiccation occurring in the remaining leaf
- 15% of the “tops” (cabbage) material is burned, and a degree of desiccation also occurs in the remaining product

While the pre-harvest burn will have some impact on levels of sour cane\(^{50}\) and dry cane, this effect is ignored in the analysis, and these components are assumed to be part of the cane supply.

Table 3-7 presents a dataset for the base case of burned cane, assuming a pre-harvest yield of 107 tons per acre cane stalk, with the effect of burning as indicated above, and the levels of incorporated soil and inorganic material as indicated in the inputs to the model.

<table>
<thead>
<tr>
<th>Table 3-7: Pre-harvest cane component mass and component mass delivered to mill washing plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-Harvest Crop Characteristics for burned crop (t/ac)</strong></td>
</tr>
<tr>
<td>At-harvest clean cane stalk</td>
</tr>
<tr>
<td>Total Leaf and Tops (fresh weight)</td>
</tr>
<tr>
<td>Tons in field at Harvest</td>
</tr>
<tr>
<td><strong>Product Delivered to Mill Cleaning Plant (t/ac)</strong></td>
</tr>
<tr>
<td>Clean cane stalk</td>
</tr>
<tr>
<td>Leaf and Tops (fresh weight)</td>
</tr>
<tr>
<td>Soil and inorganic material</td>
</tr>
<tr>
<td>Total Product Delivered</td>
</tr>
</tbody>
</table>

\(^{50}\) “Sour cane” is cane stalk which is damaged or diseased, but still moist.
Further analysis of the product flow is presented in Table 3-8. It illustrates the flow of mass of different cane components from mill delivery to the shredder.

<table>
<thead>
<tr>
<th>Table 3-8: Flow of mass of different cane components from mill delivery to the shredder</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product delivered to mill</strong></td>
</tr>
<tr>
<td>Clean cane stalk [t/ac]</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight) [t/ac]</td>
</tr>
<tr>
<td>Soil and inorganic material [t/ac]</td>
</tr>
<tr>
<td><strong>Total product delivered [t/ac]</strong></td>
</tr>
<tr>
<td><strong>Cleaning System: Washing</strong></td>
</tr>
<tr>
<td><strong>Product Removed (by mass)</strong></td>
</tr>
<tr>
<td>Clean cane stalk components [t/ac]</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight) [t/ac]</td>
</tr>
<tr>
<td>Soil and inorganic material [t/ac]</td>
</tr>
<tr>
<td><strong>Total product removed / lost [t/ac]</strong></td>
</tr>
<tr>
<td><strong>Product to shredder</strong></td>
</tr>
<tr>
<td>Clean cane stalk [t/ac]</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight) [t/ac]</td>
</tr>
<tr>
<td>Soil and inorganic material [t/ac]</td>
</tr>
<tr>
<td><strong>Total product to shredder [t/ac]</strong></td>
</tr>
<tr>
<td><strong>Net cane stalk delivered to shredder [t]</strong></td>
</tr>
<tr>
<td><strong>Total product to shredder per harvest [t]</strong></td>
</tr>
</tbody>
</table>
Table 3-9 presents the assumed flow of recoverable sucrose, based on the Australian “CCS” method\(^{51}\) of determining recoverable sugar.

<table>
<thead>
<tr>
<th>Table 3-9: Recoverable sucrose in product flow field from sucrose at harvest to recovered sugar in burned cane base case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable sucrose in stalk (%)</td>
</tr>
<tr>
<td>Tons clean stalk/acre</td>
</tr>
<tr>
<td>Tons sugar/acre</td>
</tr>
</tbody>
</table>

**Sucrose Pre-cleaning**

| Recoverable sucrose in clean stalk              | 16.21% |
| Tons stalk/acre                                 | 97.4   |
| Tons sugar/acre\(^{52}\)                        | 15.78  |

**Sucrose Entering Milling Train**

| Recoverable sucrose in stalk                   | 13.6%  |
| Tons stalk/acre                                | 91.5   |
| Tons sugar/acre                                | 12.46  |

**Sugar Recovered**

| Tons sugar/acre recovered                      | 12.22  |
| Total sugar recovery (tons/year)               | 199,874|

**Fiber**

| Fiber in bagasse (t/acre)                      | 14.05  |
| Total fiber recovery (tons)                    | 229,737|

**Milling Rate**

| Acres/hour to be harvested @ 50 t/hr           | 3.56   |
| Days to harvest 16,350 acres @ 80% time efficiency | 236    |

\(^{51}\) The Australian CCS formula determines recoverable sugar at a sugar mill from juice analysis and fiber content, along with empirical factors relating to commercial sucrose recoveries. For comparative purposes, it gives similar results to a number of formulae used to derive estimated recoverable crystal.

\(^{52}\) The tons sugar/acre at delivery is the pre-harvest tons sugar/acre less direct and indirect harvesting losses.
Table 3-9 indicates the assumed sugar recovery and fiber production, along with a derived season-length assuming 50 tons per hour fiber milling capacity and 80% overall milling time efficiency, as the “base case” for further analysis.

### 3.3.6 Agronomic Sustainability of Option #1: Two-Year Sugarcane, Burned for Harvest

The current crop production system has been utilized in Hawaii for many years, with nominally stable productivity. Water availability is seen as the most significant factor impacting on yields. The current production system is based on:

- The production of sugarcane as a monoculture
- Almost complete removal of above-ground biomass and a significant removal of roots and other sub-surface materials during the harvest operation
- High levels of random traffic across the field

  The extent of compaction varies with the equipment involved. Tracklayer tractors used for windrowing have a moderate compactive effect. Cane haulage units along the cane haulage tracks in each field have an extreme compactive effect.

- Aggressive tillage processes undertaken on a bi-annual basis to replant the crop

  The short time window available means that there is little or no opportunity to allow natural processes to facilitate the land preparation process. Therefore, the required soil tilth must be achieved by mechanical manipulation of the soil.

Research in Australia has indicated that the “Yield Plateau” which has been observed in the Australian industry since the early-1970s has been predominantly a soil health effect (Garside\textsuperscript{53}). The move to farming systems which result in pro-active strategies to improve soil health have resulted in significant improvements in water-use efficiency by the crop, typically resulting in increased yield under water deficit cropping conditions.

While these issues are likely to be of very significant interest to the HC&S sugar production operation, further discussion is beyond the scope of this report.

Some HC&S soils are classified as moderately sloping and erodible, however the potential for erosion is somewhat mitigated by the rapid turnaround between crop-cycles and the two-year crop controlling harvest and land preparation operations.

### 3.3.7 Option #1 Summary: Two-Year Sugarcane, Burned for Harvest

Table 3-10 summarizes some key outputs generally representing the current crop production system. Approximately 200,000 tons of sugar can be produced from an area of 16,350 acres harvested per year, on a two-year cropping system. This equates to a nominal productivity of 5.67 t\textsubscript{s} per farmed acre per year (harvested area plus area farmed for seedcane), or an “agronomic yield” of approximately 6.5 t\textsubscript{s} per harvested acre after correcting for average crop age and area harvested for milling.\textsuperscript{54}

<table>
<thead>
<tr>
<th>Table 3-10: Summary of key parameters relating to a production system based on current practices in the Hawaiian Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmed Area (acres)</td>
</tr>
<tr>
<td>Annual Harvest (acres)</td>
</tr>
<tr>
<td>Estimated Product Tonnage Transported to Mill (t/acre)</td>
</tr>
<tr>
<td>Annual Fiber Production (dry, ash free) in Bagasse</td>
</tr>
<tr>
<td>Annual Sugar Production (t)</td>
</tr>
<tr>
<td>Annual Sugar Production/Gross Farmed Acre</td>
</tr>
</tbody>
</table>

\textsuperscript{54} The Activity 2 report was premised on the following key parameters.

| Farmed Area (acres) | 32,992 acres |
| Annual Harvest (acres) | 16,476 acres |
| Estimated Product Tonnage Transported to Mill (t/acre) | 102 ton/acre |
| Annual Fiber Production (dry, ash free) in Bagasse | 249,776 tons |
| Annual Sugar Production (t) | 201,007 tons |
| Annual Sugar Production/Gross Farmed Acre | 6.09 t\textsubscript{s}/acre/year |

The parameters vary between the Activity 2 and Activity 3 analyses for a number of reasons. A primarily reason relates to variations in the amount of land planted and harvested each year, and the length of the historical perspective taken by the two researchers. In addition to normal variability, HC&S acreage varies because it leases some of its property and/or permits (and/or conducts) research on its land.
The crop-cycle is typically two years between replants, with only a very small proportion of the harvested crop being ratooned. Analysis of the crop production and harvesting systems indicate mechanically aggressive processes.

The yields of recovered sugar on productivity per farmed acre per year are lower than yields achieved on some other large scale industries. All harvest and transport systems have losses, and mechanization usually equates to a balance between losses and costs. While arguable low cost, the Hawaiian harvest and transport system and associated washing plants result in only approximately 55% of the sucrose produced by the crop being recovered at the mill. These losses are significantly greater than losses with other mechanized systems, and substantially greater than manual based systems. This substantially impacts on recovered sugar yields in Hawaii relative to other sugar industries, and thus Hawaiian Industry profitability.

Aside from the impact of management decisions on crop inputs, yields at the Maui plantation have been stable for many years. Water availability is named by staff as the most significant factor impacting on crop productivity. Despite this nominally stable productivity, it is likely that the current crop production system has resulted in declining soil organic matter levels and increasing levels of plant parasitic organisms in the soil (Garside et al.). While these factors do not necessarily negatively impact on yields under high levels of inputs, the impact on yield under sub-optimal conditions is much more dramatic (Garside). These issues need further investigation.

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3.4 Crop Option #2: Two-year Sugarcane, Unburned for Harvest

To increase the total available fiber for alternative industrial processes, one strategy is to retain the current two-year harvest production system, but eliminate the pre-harvest burn. This strategy is currently used by HC&S on a limited scale when environmental conditions or “good neighbor” considerations dictate that a field not be burned prior to harvest. The impact of a large scale move to two-year unburned cane will have varying degrees of impact on:

- The crop production system
- The harvesting and haulage system
- The industrial processes, i.e., milling and sugar recovery

This harvesting strategy would allow the recovery of leaf material from the field to be maximized. The net thermal value of the product would be affected by the wetting of the leaf material, which occurs as it passes through the cane washing plant and/or milling process, and the total recoverable energy by the net thermal value and actual recovery of leaf.

3.4.1 Production System: Two-Year Unburned Sugarcane

The impact of a move to two-year unburned harvesting cycles on a crop production system can be anticipated to include the following.

- Land preparation practices will remain essentially the same as current practices, however some burning or spreading of remnant trash may be necessary prior to the commencement of land preparation practices.

- It is anticipated that the percentage of fields which can be ratooned effectively may be further reduced, because of potentially even greater loss of plant stool associated with green cane harvesting. This effect is anticipated because of higher friction between green cane stalks (relative to burned cane stalks) during any harvesting operation resulting in greater stress being transferred into the cane stool (Schembri and Garson)\textsuperscript{56}. Higher stress transferred into the stool can be argued to equate to greater stool removal during harvesting.

It is therefore anticipated that the move to a system where the crop is not burned prior to harvest will:

• Potentially result in some further reduction in the potential for economic ratooning of crops

• Result in a small increase in land preparation costs because of increased trash levels remaining in the field potentially requiring some spreading or post-harvest operation

The combined effects are anticipated to be of a magnitude wherein there will be relatively minimal impact on overall crop production costs.

3.4.2 Defining the Characteristics of Unburned Sugarcane

The components of a sugarcane plant prior to harvest can be broadly categorized as:

- Green leaf
- Tops, or the “cabbage” component of leaf surrounding the growing point
- Dry leaf
- Cane stalk
- Damaged (“sour”) and dry/dead cane stalk, typically resulting from damage
- Root mass and associated soil

In addition to the inherent range in component mass, considerable variability and misinterpretation also occurs in the measurement of cane components and the allocation into component classes. It should be noted that in reported trial results, “trash” can imply anything from “brown leaf only” to “all cane components except sound millable stalk”.

Chen57 notes that “Cane trash, by ISSCT definition, is the leaves, tops, dead stalks, root, soil, etc., delivered at the factory with the net clean cane.” While this definition is appropriate for analysis of milling performance, it is less useful for other analyses. The increasing interest in sugarcane as a biofuel has accelerated the trend of referring to this material as “Extraneous Matter” (“EM”). Increasingly, trash is being defined as only the green leaf and dry leaf components of the plant.

Some data sets from Hawaiian research, e.g., Evensen’s work (discussed extensively in Activity 2), follow the International Society of Sugar Cane Technologists (“ISSCT”) recommendation, with all non-cane components (except green leaf and tops) being classified as “trash”. This creates some confusion relating to the impact of burning or not burning the crop on recoverable fiber.

The impact of green cane harvesting on biomass recovery relative to current practices is dependent on the differences in mass of different components before and after a fire.

### 3.4.2.1 Hawaiian Data

Research has also been undertaken to quantify the typical mass of cane stalk and non-cane stalk biomass both during crop growth and at harvest in Hawaii, as indicated in Activity 2. Table 3-11 presents a summary of data from 10 trials undertaken by Kinoshita. The data indicates that the fresh weight of tops and green leaf averaged 4.8% and dry leaf 9.3% of the fresh weight of the pre-harvest biomass in the field; totaling 14.1% for these components. The fresh weight of dead and “sour” cane contributed approximately 7.5% of the fresh weight. While this material would nominally be called “trash” it is currently delivered as part of the cane supply.

Analysis of fiber weights in Kinoshita’s data indicates that dry leaf contributes approximately 34% of the total fiber at harvest, with green leaf and tops contributing approximately 5.6%. While most of the dry leaf will be destroyed in the pre-harvest burn, the impact on green leaf and tops will be less easy to define.

### 3.4.2.2 Other Data

To determine the relativity of dry leaf and green leaf levels, alternative data should also be assessed. Figure 3-20 gives an example (Thurbon et al.) of the range in fresh weight anticipated for tops and leaf immediately prior to harvest in a range of crops in two cane growing areas in Australia, in both irrigated and rain-fed conditions.

The data illustrates the very significant range in fresh weight of both trash and tops components. However, the trend lines applied to the data by the researchers indicate that, in the crop size range anticipated in Hawaii (e.g., 100 to 110 t/ac):

- Fresh weight of tops will be approximately 7 to 8 tons per acre (15 to 17 t/ha), with a range of +/- 25% of this value

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### Table 3-11: Composition of unburned Hawaiian cane (%) by component and constituent

<table>
<thead>
<tr>
<th>Sugarcane Constituent</th>
<th>Net Cane</th>
<th>Sour Cane</th>
<th>Dead Cane</th>
<th>Green Leaves and Tops</th>
<th>Dry Leaves and Trash</th>
<th>Percentage (weighted) Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Wt. of Components (t/ac)</td>
<td>118.4</td>
<td>8.5</td>
<td>2.9</td>
<td>7.2</td>
<td>14</td>
<td>151</td>
</tr>
<tr>
<td>Fresh Wt. % Contribution to Components</td>
<td>78.4</td>
<td>5.6</td>
<td>1.9</td>
<td>4.8</td>
<td>9.3</td>
<td>100</td>
</tr>
<tr>
<td><strong>Fiber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In component (t/ac)</td>
<td>12.3</td>
<td>14.2</td>
<td>22.3</td>
<td>21.0</td>
<td>65.6</td>
<td>18</td>
</tr>
<tr>
<td>Contribution (%)</td>
<td>56.3</td>
<td>4.5</td>
<td>2.4</td>
<td>5.6</td>
<td>34</td>
<td>100</td>
</tr>
<tr>
<td><strong>REFSOL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In component (t/ac)</td>
<td>16.3</td>
<td>10.8</td>
<td>6.3</td>
<td>6.9</td>
<td>6.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Contribution (%)</td>
<td>88.5</td>
<td>4.2</td>
<td>0.8</td>
<td>2.3</td>
<td>4.2</td>
<td>100</td>
</tr>
<tr>
<td><strong>POL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In component (t/ac)</td>
<td>14.6</td>
<td>6.8</td>
<td>1.4</td>
<td>2.3</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>Contribution (%)</td>
<td>95.1</td>
<td>3.2</td>
<td>0.2</td>
<td>0.9</td>
<td>0.5</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: The gross fresh weight of the biomass was 151 tons/acre
Source: Kinoshita (1985); Activity 2
• Fresh weight of leaves will be approximately 10 to 11 tons per acre (22 to 24 t/ha), with a similar range in values

Further analysis of data from a number of researchers (Mitchell\textsuperscript{60}, De Beer\textsuperscript{61} and Cock\textsuperscript{62}) indicates similar average values, with factors such as crop variety, cane “class” (plant-crop or ratoon-crop), crop maturity at harvest, and various environmental and climatic factors impacting on cane plant composition immediately pre-harvest.

![Figure 3-20: Observed fresh weight of tops and green leaf and dry leaf over a range of sites in two different environments in Australia (Thurbon et al.)](image)

Evensen’s work (as discussed in Activity 2) reports on the progression of the fresh weight of leaf material as the crop develops and matures. The data indicates a rapid reduction in the fresh weight (“FW”) biomass of tops and green leaf as the plant age.


increases from 12 months, and a further more subdued reduction in the period 18 to 24 months, possibly associated with the maturation process. This can also be argued to be consistent with differences resulting from plant breeding strategies for “one-year” and “two-year” canes.

The magnitude of biomass associated with tops and green leaf and dry trash (brown leaf) can therefore be argued to be similar for both the Australian work of Thurbon and Kinoshita, despite the impact of the lower crop age anticipated in Thurbon’s observations of one-year cane. Varietal effects can be argued to dramatically impact on this, with Hawaiian varieties potentially having trash levels in the upper range of that associated with varieties typically used in other industries around the world, including Australia.

“Typical” trash biomass levels for “two-year cane” in Hawaii can then be assumed as follows: green leaf and tops: 4 to 6% of total biomass on fresh weight basis
dry leaf: 8 to 10% of total biomass on fresh weight basis

3.4.3 Harvesting Productivity and Cost

Trials in South Africa (De Beer et al.)\(^6^3\) assessed the impact of different harvesting treatments on harvesting and transport system productivity. The treatments were:

- Burned and topped
- Burned and not topped
- Unburned and topped
- Unburned and not topped.

The variety was NCO 376, which is known as a variety with relatively high levels of tops biomass. The reported yield was 55 t/ac and crop age 19 to 20 months. Analysis of data indicates fresh weight of dry leaf trash at 8% of total harvested biomass and tops and green leaf at 14%. The trash levels are slightly lower than noted under Hawaiian conditions, and the levels of tops are slightly higher. Table 3-12 compares the results of the “unburnt and untopped” treatments with “burnt and untopped” treatments in the De Beer trials.

Table 3-12: Impact of burning or not burning on loading rate and payload

<table>
<thead>
<tr>
<th></th>
<th>Gross Loading Rate (tonnes/hr)</th>
<th>Gross Transport Payload (tonnes)</th>
<th>Clean Cane Payload (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burned and Not Topped</td>
<td>31.9</td>
<td>24.9</td>
<td>22.7</td>
</tr>
<tr>
<td>Unburned and Not Topped</td>
<td>21.7</td>
<td>18.3</td>
<td>14.1</td>
</tr>
<tr>
<td>% of Burned Loading Rate/Payload</td>
<td>68%</td>
<td>73%</td>
<td>62%</td>
</tr>
</tbody>
</table>

Source: De Beer et al.28

Table 3-12 illustrates that with the cane conditions nominated; the impact of not burning was as follows.

- Loading rate of “cane + tops + trash” was 68% of the loading rate achieved with “cane + tops” only. Conversely, the unburned treatment increased the time required for loading by 47%.

- Trailer payload with “cane + tops + trash” was 73% of the payloads achieved with “cane + tops” only. Conversely, the unburned treatment increased the number of transporter loads by 37%.

- Clean cane payload of the “cane + tops + trash” loads was 62% of the clean cane payload of the “cane + tops” treatment.

- For reference purposes, the “burnt and topped” treatment in these trials had a payload of 27.8 tons (25.2 tonnes) of clean cane.

In work by Eiland and Clayton64 on machine harvesting unburned crops, they noted previously published work:

“Orsenigo reported on problems in hand harvesting unburned cane and determined production rates for unburned and burned cane. He concluded that 50 percent more workers, 200 percent more

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continuous loaders, and 50 percent more transport capacity would be needed to harvest unburned cane than to harvest burned cane”.

The trash levels being assumed for Hawaiian conditions are approximately 20% higher than those measured in the De Beer trials, and this can be anticipated to impact on loading and transport operations. Based on the experience of lead researcher Chris Norris, as a result of input into trials in the Philippines, South Africa, and Swaziland, operators derived strategies to minimize the load density impact of green cane. The following is assumed under Hawaiian crop conditions and with different machine selection.

- Windrowing costs will increase by a somewhat lesser amount than the De Beer trials, because of the potential for optimization of the push-rakes for unburned cane. A 30% increase in costs/gross ton is assumed.

- Similarly, it is assumed that some optimization of loader productivity will be achieved, despite the higher trash levels. Loading productivity (tons of total product) of “cane + tops + trash” will be assumed to be reduced by an approximately similar amount to that indicated in the De Beer trials. A 45% increase in cost per ton loaded is assumed.

- In relative terms, haulage costs per ton will increase by approximately 35% (on a gross tonnage basis), because it is primarily a volumetric operation.

The impact of green cane harvesting on the harvest and transport operation will be significant, and can be assessed on the basis of the impact on the components of the operation. The anticipated harvesting costs based on the assumed harvesting cost for burnt cane are presented in Table 3-13.
Table 3-13: Estimated harvesting and transport costs associated with an unburned two-year crop

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost/t</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-harvest Burn</td>
<td>$0/t</td>
<td>This operation is no longer undertaken.</td>
</tr>
<tr>
<td>Windrowing with D8 Tractors</td>
<td>$1.95/t</td>
<td>It is assumed that the cost of this operation will increase by approximately 30% because of reduced product density and larger windrows because of increased total biomass.</td>
</tr>
<tr>
<td>Loading with Hydraulic Grab Loader</td>
<td>$1.81/t</td>
<td>Based on anticipated reduction in mass loading rate after allowance for some machine optimization, the reduction in productivity is assumed at 45%.</td>
</tr>
<tr>
<td>Cleanup after Loading</td>
<td>$0.50/t</td>
<td>Similar to current cost.</td>
</tr>
<tr>
<td>Cane Transport</td>
<td>$4.46/t</td>
<td>Based on a 35% reduction in payload because of reduced load density.</td>
</tr>
<tr>
<td>Total Cost per Ton Product Delivered</td>
<td>$8.72/t</td>
<td></td>
</tr>
</tbody>
</table>

This analysis indicates an increase in harvesting costs on a per ton basis from $6.60 to $8.72 for the higher levels of biomass associated with unburned crops.

Table 3-14 illustrates the anticipated differences in material delivered to the mill associated with the different harvesting strategies.

Table 3-14: Tonnage of product transported to mill for burned cane and green cane scenarios

<table>
<thead>
<tr>
<th>Pre-Harvest Crop Characteristics (t/ac)</th>
<th>Burnt</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>At-harvest clean cane stalk</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>Total leaf and tops (fresh weight)</td>
<td>4.5</td>
<td>19.9</td>
</tr>
<tr>
<td>Tons in field at harvest</td>
<td>112</td>
<td>127</td>
</tr>
<tr>
<td>Product Delivered to Mill (t/ac)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean cane stalk</td>
<td>97.4</td>
<td>97.0</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight)</td>
<td>4.1</td>
<td>17.5</td>
</tr>
<tr>
<td>Soil and inorganic material</td>
<td>6.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Total product delivered</td>
<td>107.6</td>
<td>122.0</td>
</tr>
</tbody>
</table>
The reductions in harvesting productivity, in association with the increased biomass tonnages, will directly transfer into increases in the cost of the harvesting operation. The cost associated with each scenario is then:

- Burnt cane: \(107.6\, \text{t/acre} \times \$6.60/\text{t} = \$710/\text{acre}\)
- Unburned cane: \(122.0\, \text{t/acre} \times \$8.72/\text{t} = \$1,063/\text{acre}\)

On the basis of an assumed harvested area of 16,350 acres, total annual harvest and transport-to-mill cost has therefore increased from $11,610,000 to $17,389,000; an increase of $5,778,000 or approximately 50%.

### 3.4.4 Mill Throughput and Sucrose Recovery

Current burnt-cane harvesting techniques used in Hawaii result in significant levels of soil, rock and other materials being forwarded to the sugar milling facility. Available information and visual observations indicate relatively low levels of leaf and other non-sucrose material are forwarded to the mill. Cane laundries or washing plants are successfully used for the removal of significant proportions of soil and inorganic material (rocks, etc.) from cane delivered to the milling facility. This results in relatively clean product being forwarded for the preparation and extraction processes.

The current HC&S process makes no attempt to remove the “tops”, and limited attempt to remove any other leaf material with the cane; this is also forwarded to the mill. With burned, ripened cane, the “non-cane” material is ripened tops with relatively small levels of leaf material. This will change significantly with a move to unburned cane harvesting. The move to unburned cane would result in a significant increase in the organic material (leaf, tops, etc.) being forwarded to the milling process relative to current practices.

It is anticipated that while significant proportions of entrained soil and rock will be removed by the wet laundries, performance may well be reduced relative to their performance with burnt cane. There is a greater potential for entrapment of soil, because of the higher volumes and surface areas of material and component characteristics; i.e., leaf material are more likely to entrap soil than clean stalk, resulting in higher concentrations of soil being carried through to the milling train.

Even if the impact of trash on cane cleaning plant performance is ignored, the impact of moving from the current burnt-cane system where “burnt cane + tops” are milled, to a system where “unburned cane + tops” are milled, will be significant because of the:

---

65 Assumed annual harvest of 16,350 acres.
- Increase in fiber associated with both the dry trash and semi-dry “green leaf”, which is typically burned in the fire

- Increase in non-POL components in the product being sent to the process house

Trials conducted by Reid and Lionnet\(^66\), in conjunction with the trials conducted by DeBeer et al.\(^67\) looked at the impact of the different trash levels associated with different treatments on a number of milling parameters. The numbers relating to milling performance are presented in Table 3-15.

<table>
<thead>
<tr>
<th></th>
<th>Milling Rate</th>
<th>Bagasse % cane (Fiber % cane)</th>
<th>Milling rate: bagasse (t/hr)</th>
<th>Milling Train Extraction (%)</th>
<th>Boiling House Recovery (%)</th>
<th>Overall Sucrose Recovery (%)</th>
<th>Relative Sugar Recovery (%)</th>
<th>Sugar Production Rate (t/hr)</th>
<th>“A” Sugar Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burnt and Topped</td>
<td>180.6</td>
<td>32.1 (14.4)</td>
<td>58</td>
<td>96.7</td>
<td>91.3</td>
<td>88.3</td>
<td>100%</td>
<td>21.6</td>
<td>870</td>
</tr>
<tr>
<td>Unburnt, Untopped</td>
<td>127</td>
<td>48.34 (21.7)</td>
<td>61.4</td>
<td>96.3</td>
<td>83.7</td>
<td>80.6</td>
<td>92.3%</td>
<td>10.9</td>
<td>1784</td>
</tr>
</tbody>
</table>

The data indicates the following.

- An approximately constant bagasse production rate by the milling train, with increasing trash levels having limited impact on milling train extraction and a highly significant impact on milling rate.

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• The increasing trash levels significantly reduced boiling house recovery and overall sucrose recovery.

• The sugar production rate was affected by both the reduced cane crushing rate and the lower boiling house recovery at the high trash levels.

• Sugar color appears to be highly correlated with the presence of leaf trash.

Further analysis indicates that, assuming nominally similar fiber levels in the bagasse (assumed “Fiber % Bagasse” = 46%) from different treatments is as follows.

• The increase in trash provides an increase in the percentage of fiber in the incoming product from 14.8 to 22.3%, an increase of 51%.

• The overall sucrose recovery is reduced from 88.3 to 80.6%. The higher trash level results in an 8.7% reduction in total sucrose recovery.

• The trend defined by the results can be defined as follows.
  o A 51% increase in fiber coincides with an 8.7% reduction in sugar recovery.

  This equates to:
  o Each 10% increase in fiber levels in the milled product results in a 1.7% reduction in sucrose recovered.

Other researchers have also studied the impact of this increase in non-cane product on various aspects of milling and sucrose recovery. The following are some findings.

• While not observed in the results from Lionnet et al., losses to bagasse are nominally related to bagasse production. Kent\(^68\) quotes findings from a number of researchers indicating “POL % bagasse” typically remains constant, or even increases as trash fiber increases in the bagasse. Kent observed similar results in trials at Mossman Mill in Australia.

• Research typically indicates higher losses to bagasse and higher bagasse moisture content as trash levels increase, even when fiber crushing rate is

maintained as a constant. Assuming constant “sucrose % fiber”, the increase in fiber loadings of 50% will increase sucrose losses to bagasse at least proportionally. As with the Lionnet findings, Kent observed that the fiber milling rate remained near-constant as trash levels varied.

- In a series of trials in 2010 in Australia, Kent et al.\(^{69}\) notes that on average “for each percentage unit of fiber introduced by leaf material, the total sucrose recovery (sucrose % total milled product) is reduced by between 0.9 and 1.5 percentage units”. He further notes that the largest losses were associated with increased molasses production, followed by losses to filter mud and then bagasse.

- Further findings from these trials indicated that the primary impact of high trash levels was the high non-POL product entering the boiling house. Apart from reduced recoveries and increased molasses production, a reduced rate of crystallization significantly reduced commercial sugar production rates (Farrell, Chief Engineer, Broadwater Mill, NSW Sugar, personal communication).

The move to “whole cane” milling, as a strategy to increase fiber available for cogeneration by the Northern NSW mills in Australia, was abandoned because of the magnitude of the sugar losses encountered (Farrell). Milling train capacity had been increased to counter the reduction in mill throughput associated with increased fiber loadings. This was despite the significant upgrade in shredding and milling train capacity which had been installed.

Further research is therefore required to define mill-related losses associated with a move to green cane harvesting.

### 3.4.5 Predicting Reductions in Milling Recovery with Increased Trash Levels

To model the impact of increasing trash levels on milling performance, the primary assumptions are as follows.

- Mill fiber crushing rate will remain approximately constant as fiber rate changes.

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- Losses of POL in bagasse will be approximately proportional to bagasse production.

- Losses to molasses will increase, as will losses to filter mud.

For the purposes of assessing sucrose recovery, the averaged result of three strategies of sucrose loss estimation can be used.

1) The results from the trials undertaken by Lionnet, where an overall increase in fiber in the cane supply of 10% (e.g., 12% fiber to 13.2% fiber) results in a 0.17% reduction in the mass of recoverable sucrose.

2) The results from Kent et al., where a one unit increase in “fiber % cane” (e.g., 12% fiber to 13% fiber) resulted in a 1 to 1.6 unit reduction in “CCS”\(^{70}\) (i.e., sucrose recovered as a percentage of milled material.

3) Calculation of the anticipated loss based on an estimation of the components of loss. Losses to bagasse are assumed to increase in proportion to total fiber in the product being milled, with nominally equivalent losses to both molasses and filter mud.

Under a range of different levels of extraneous matter, all three methods can be shown to give similar trends in sucrose loss, with the Lionnet trials typically giving the highest indicated losses.

### 3.4.6 Strategies to Minimize Losses Associated with Increased Trash Levels

The move to green cane harvesting at HC&S with the current harvest system therefore offers a choice of either of the following.

1) A significant reduction in milling capacity, which can only be partially managed by increasing milling train capacity and potentially significant modifications to the process house.

or

2) Utilization of systems to remove the highest practical proportion of leaf material prior to the milling process to minimize the impact on the mill.

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\(^{70}\) “CCS is the method used by the Australian Industry to determine recoverable sugar in cane delivered to the mill. It assumes “typical” mill sucrose recovery efficiencies
Technology has been utilized in the past to address this problem. Sniffen\textsuperscript{71} noted:

“The Olsen rolls, one of the most prominent extractors used, seem to be quite effective. However, the cane which is lost by being drawn through with the trash causes considerable concern and there is doubt among some mill people as to whether the advantage gained by this trash extracting process is not offset by the loss of cane.”

Taylor\textsuperscript{72} noted that considerable further development was undertaken on the system, and reported that results improved very significantly. It was also reported that the use of high pressure water jets between rollers improved trash extraction efficiency. Improvements in mill performance by the operation of “optimized” Olsen Rolls, as noted by Taylor included:

- Less wear on mill rolls by reduction of entrained dirt
- Increase in purities of mixed juice
- Easier clarification
- Twenty-five per cent increase in net cane grinding rate
- Better mill extraction

These findings are all consistent with the anticipated impact of the reduction in leaf trash levels entering the milling train. However, little “hard” data is available to indicate the actual trash extraction levels achieved or the actual levels of cane loss which were suffered by the utilization of the “improved” Olsen Rolls.

Figure 3-21 illustrates a cane cleaning plant roller. Rollers of similar diameter, although of less aggressive profile, would be utilized in an Olsen Roll installation. Based on descriptions of the process in the limited available literature, and in conjunction with observations of a similar concept in mills in Peru by lead researcher Chris Norris, the following is indicated.

The units are effective in achieving significant loose trash (dry leaf) removal; however the actual levels of extraction will depend on a number of interacting factors. Under optimum conditions of loose trash and good operating conditions, trash extraction levels may exceed 80%. However, under “normal” operating conditions, extraction efficiency will be lower.

\textsuperscript{71} Sniffen, Samuel A. Improvements in Olsen Roll Operation at HC&S Co. Chemical and Engineering Section, Hawaiian Sugar Technologists.

\textsuperscript{72} Taylor, Dennis. Results from Hutchinson Adaptation of Olsen Rolls (1953) Chemical and Engineering Section, Hawaiian Sugar Technologists: 83-84.
Assuming optimized design, and in the absence of quantitative data, a nominal trash extraction efficiency of 60% can be assumed as realistic.

Figure 3-21: The rollers utilized in an Olsen Roll installation would be similar in diameter to this “Giago” used to transfer cane across the sink-float tank.

Figure 3-22: Drip tape wrapping around rolls in the cleaning plant

- Green leaf removal will occur in conjunction with the removal of tops, with the tops being broken from the cane stalk by the action of the rolls on the green leaf. The aggressive use of water jets will potentially increase green leaf “capture”; however overall removal will be lower than dry leaf removal. Green leaf and tops removal of 40% is assumed as realistic, in the absence of quantitative data.

- Cane loss will be an inevitable component of the process, as a relatively small proportion of tops will break at the “natural break point”. Small pieces of cane will also be lost. For the purposes of initial analysis, it is assumed that the incorporation of Olsen Rolls will increase the mass of cane lost through the cane cleaning process by at least 5% of delivered cane.

- Drip irrigation tape incorporated in the delivered cane could potentially be a significant issue, wrapping around the rollers and rendering them less efficient with respect to trash removal. The wrapping potential of drip irrigation tape is illustrated in Figure 3-22.
The removal of leaf components will at least partially mitigate the negative impact of trash on the extraction of soil and small rock material.

3.4.7 Cane Mass and Composition Resulting from Different Strategies

Table 3-16 presents a Mass Balance of product flows delivered to the mill from the two harvesting processes. The unburned cane is then either passed through the standard washing plant or passed through a washing plant incorporating Olsen Rolls. The mass composition of the product being forwarded to the shredder is then derived by incorporating the separation levels and losses to each crop component associated with each process.

<table>
<thead>
<tr>
<th>Product Delivered to Mill</th>
<th>Burnt</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk (t/ac)</td>
<td>97.4</td>
<td>97.4</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight t/ac)</td>
<td>4.1</td>
<td>17.5</td>
</tr>
<tr>
<td>Soil and inorganic material (t/ac)</td>
<td>6.1</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Total product at delivery (t/ac)</strong></td>
<td><strong>107.6</strong></td>
<td><strong>121.9</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cleaning System: Product Removed (by mass)</th>
<th>Washed</th>
<th>Washed</th>
<th>Wash + Olsen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk (t/ac)</td>
<td>5.8</td>
<td>5.8</td>
<td>8.8</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight t/ac)</td>
<td>0.4</td>
<td>3.2</td>
<td>9.2</td>
</tr>
<tr>
<td>Soil and inorganic material (t/ac)</td>
<td>5.5</td>
<td>4.7</td>
<td>6.3</td>
</tr>
<tr>
<td><strong>Total product removed / lost (t/ac)</strong></td>
<td><strong>11.7</strong></td>
<td><strong>13.7</strong></td>
<td><strong>24.3</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product to Shredder</th>
<th>Washed</th>
<th>Washed</th>
<th>Wash + Olsen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk (t/ac)</td>
<td>91.5</td>
<td>91.5</td>
<td>88.6</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight t/ac)</td>
<td>3.7</td>
<td>14.4</td>
<td>8.3</td>
</tr>
<tr>
<td>Soil and inorganic material (t/ac)</td>
<td>0.6</td>
<td>2.3</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total product to shredder (t/ac)</strong></td>
<td><strong>95.9</strong></td>
<td><strong>108.2</strong></td>
<td><strong>97.6</strong></td>
</tr>
<tr>
<td><strong>Annual tonnage to shredder (t)</strong></td>
<td><strong>1,567,600</strong></td>
<td><strong>1,768,500</strong></td>
<td><strong>1,569,200</strong></td>
</tr>
</tbody>
</table>

The data derived from the anticipated performance of the washing system, with the option of the inclusion of Olsen Rolls, indicates the following.

- A reduction in cane stalk mass associated with the Olsen Rolls.
• Levels of leaf and tops range from 3.7 t/ac for burned cane to 14.4 t/ac for unburned cane without the Olsen Rolls. The Olsen Rolls are assumed to reduce trash levels to 8.3 t/ac.

• There is an increase in soil and inorganic material in the product from unburned cane harvesting and wash only. This is due to the anticipated impact of the trash on soil removal. However, this is assumed to be effectively mitigated by the effect of the Olsen Rolls.

• Final tonnage entering the shredder is similar for the Olsen Rolls and burnt-cane assumptions (although the composition is different), and highest for unburned and washed cane.

3.4.8 Product Recovery

Factors impacting on the sucrose production associated with the different scenarios will include the following:

• Losses associated with physical cane mass loss during processes such as harvest and cane washing, with additional losses associated with trash separation, e.g., the Olsen Rolls system

• Deterioration and leaching losses, such as the losses associated with pre-harvest burning, the harvesting operation, and losses in the cane washing facility

• Losses in the milling operation, both through losses through the milling train, and losses with molasses

An overview of the losses incurred in the harvest, transport and washing processes with burned cane is covered in Section 3.3 (Crop Option #1: Two-year Sugarcane, Burned for Harvest) of this report. A total loss of sucrose between the field and sugar store of approximately 45% is indicated. Table 3-17 presents the derived sucrose flow and mass losses as the product passes from the field through the washing plant and finally through the milling process.
Table 3-17: Product mass flow and recoverable sucrose flow from the field through the cleaning and milling processes

<table>
<thead>
<tr>
<th>Cane in Field Prior to Harvest</th>
<th>Burnt Cane Washed</th>
<th>Green Cane Washed</th>
<th>Wash + Olsen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable sucrose in stalk (%)</td>
<td>16.4%</td>
<td>16.9%</td>
<td>16.9%</td>
</tr>
<tr>
<td>Tons clean stalk/acre</td>
<td>107</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>Tons recoverable sugar (t/acre)</td>
<td>17.54</td>
<td>18.08</td>
<td>18.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sucrose at Delivery for Pre-cleaning</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable sucrose in clean stalk</td>
<td>16.2%</td>
<td>16.8%</td>
<td>16.8%</td>
</tr>
<tr>
<td>Tons stalk/acre</td>
<td>97.4</td>
<td>97.4</td>
<td>97.4</td>
</tr>
<tr>
<td>Tons sugar/acre</td>
<td>15.8</td>
<td>16.4</td>
<td>16.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sucrose Entering Milling Train after Washing</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable sucrose in stalk</td>
<td>13.6%</td>
<td>14.1%</td>
<td>14.1%</td>
</tr>
<tr>
<td>Tons/stalk/acre</td>
<td>91.5</td>
<td>91.5</td>
<td>88.6</td>
</tr>
<tr>
<td>Tons sugar/acre</td>
<td>12.5</td>
<td>12.9</td>
<td>12.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sugar Recovered in Mill</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tons sugar / acre recovered</td>
<td>12.2</td>
<td>11.2</td>
<td>11.6</td>
</tr>
<tr>
<td>Field and factory loss of recoverable sucrose loss (as % of sucrose in clean fresh stalk)</td>
<td>33%</td>
<td>38%</td>
<td>36%</td>
</tr>
<tr>
<td>Total sugar recovery (tons/acre/year)</td>
<td>199,874</td>
<td>182,799</td>
<td>190,377</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiber</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber in bagasse (t/acre)</td>
<td>14.05</td>
<td>20.2</td>
<td>16.12</td>
</tr>
<tr>
<td>Fiber from Olsen Rolls (t/acre)</td>
<td></td>
<td></td>
<td>5.9</td>
</tr>
<tr>
<td>Total fiber recovered (t/acre)</td>
<td>14.05</td>
<td>20.19</td>
<td>22.01</td>
</tr>
<tr>
<td>Total fiber recovery (tons)</td>
<td>229,740</td>
<td>330,040</td>
<td>359,800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Milling Rate</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acres/hour for mill @ 50 t/hr fiber</td>
<td>3.6</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Harvest length @ 80% time efficiency</td>
<td>236</td>
<td>341</td>
<td>275</td>
</tr>
</tbody>
</table>

73 The tons sugar/acre at delivery is the pre-harvest tons sugar/acre less direct and indirect harvesting losses.
Table 3-17 indicates the following.

- The sucrose recovered in the milling operation was 12.2, 11.2, and 11.6 t/acre, relative to the recoverable sucrose in clean stalk prior to the pre-harvest burn, which is 18.08 t/acre. The losses associated with pre-harvest burn, the harvesting operation, and the cane washing operation, along with the additional milling losses associated with the additional trash in the milled cane, then equate to 33%, 38%, and 36% of the recoverable sucrose (not total sucrose) in clean cane stalk immediately prior to harvest.

- In both green cane harvesting scenarios, the total recovery of sucrose is reduced relative to burned cane, primarily because of the impact of increased losses in the mill. At the assumed performance of the Olsen Rolls, the benefits of reduced trash through the milling train more than outweighs the additional cane loss anticipated.

- Both green cane scenarios increase the amount of fiber recovered with the Olsen Rolls option; an increase of approximately 130,000 tons over the burnt-cane scenario. The reduced trash recovery in the “wash only” scenario is associated with the anticipated loss of unrecovered leaf material through the standard cane washing facility, with this leaf material lost with mud and rocks through more aggressive settings on the cleaning plant.

- Assuming a mill crushing capacity of 50 tons per hour of fiber, the required harvest rate to supply the mill is 3.6 acres per hour in burned cane, with this reducing to 3.1 acres per hour for the Olsen Roll option, and 2.5 acres per hour for unburned cane. This equates to a season-length of 236 days, at 80% overall time efficiency for the burned cane scenario, increasing to 341 days for the green cane option without Olsen Rolls. At anticipated performance, the Olsen Rolls will reduce the season-length to 275 days.

- Comparing the “Unburned Washed” with and without the Olsen Rolls, the anticipated increase in crushing rate achieved by the Olsen Rolls is approximately 24%. This is similar to the 25% improvement noted by Taylor\textsuperscript{74}.

\textsuperscript{74} Taylor, Dennis. Results From Hutchinson Adaptation Of Olsen Rolls (1953) Chemical And Engineering Section, Hawaiian Sugar Technologists :83- 84
3.4.9 Agronomic Sustainability of Option #2: Two-year Sugarcane, Unburned for Harvest

The impact of a move to unburned harvesting cycles within the two-year cropping system will have minimal impact on the sustainability of the sugarcane cropping system currently being used for the following reasons.

- The sugarcane crop is still being grown as a monoculture.
- The almost complete removal of above-ground biomass will continue.
- The levels of traffic across the fields associated with crop production operations will be maintained, and harvest traffic will actually increase by approximately 30% because of the increased biomass haulage. The number of windrows, and therefore the number of haulage tracks through the fields, may also increase.
- There will be no effective reduction in the aggressiveness of tillage programs undertaken at crop replant.

The impact of a move to two-year unburned cane will therefore have no identifiable positive impact on the sustainability of the cropping system, with some potential to accelerate the decline in soil health associated with increasing soil compaction at harvest.

3.4.10 Option #2 Summary: Two-Year Sugarcane, Unburned for Harvest

The introduction of green cane harvesting utilizing current milling strategies is directed towards increasing the total value of the product being produced, while minimizing the changes required to the overall crop production, harvesting and processing system. Initial analysis indicates that a move to green cane harvesting without other changes would result in the following:

- No significant change to agricultural production methods or crop production costs
- An increase in harvesting and cane transport costs in the order of 50%, to a cost of approximately $1,063 per acre per harvest
• An elimination of losses associated with pre-harvest firing of the crop, which is more than offset by the reduction in sucrose recovery because of the increased trash levels being processes. Sugar production would fall by approximately 9%.

• A significant reduction in the harvest rate required to supply the mill to approximately 70% of the burned cane rate, with a corresponding and unsustainable increase in season-length.

• Fiber production would increase by approximately 100,000 tons per year. The incorporation of Olsen Rolls in the washing plant, at the assumed efficiency levels would:
  • Result in higher sucrose recovery than the unmodified mill with unburned cane. However, total sugar recovery is initially estimated to be 5% lower than production from current burned cane strategies.
  • Improve the milling rate by approximately 20% relative to the green cane scenario.
    This results in a new season-length of approximately 275 days, or 13% longer than the burnt cane season-length.
  • Increase fiber production from bagasse and cane trash from approximately 230,000 tons to approximately 360,000 tons; an increase of approximately 130,000 tons.

Table 3-18 summarizes key output parameters for the harvesting and washing systems just discussed.
Table 3-18: Summary of key output parameters for different harvesting and washing systems

<table>
<thead>
<tr>
<th></th>
<th>Burnt Cane Washed</th>
<th>Green Cane Washed</th>
<th>Wash + Olsen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar Recovered</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tons sugar / acre recovered</td>
<td>12.22</td>
<td>11.18</td>
<td>11.64</td>
</tr>
<tr>
<td>Total sugar recovery (tons/year)</td>
<td>199,880</td>
<td>182,800</td>
<td>190,400</td>
</tr>
<tr>
<td>Fiber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber in bagasse (t/acre)</td>
<td>14.05</td>
<td>20.19</td>
<td>16.12</td>
</tr>
<tr>
<td>Fiber from Olsen Rolls (t/acre)</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fiber recovered (t/acre)</td>
<td>14.05</td>
<td>20.19</td>
<td>22.01</td>
</tr>
<tr>
<td>Total fiber recovery (tons/year)</td>
<td>229,700</td>
<td>330,000</td>
<td>359,800</td>
</tr>
<tr>
<td>Milling Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acres /hour for mill @ 50 t/hr fiber</td>
<td>3.6</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Harvest length @ 80% time efficiency</td>
<td>236</td>
<td>341</td>
<td>275</td>
</tr>
</tbody>
</table>

### 3.5 Crop Option #3: One-year Sugarcane and Type I Energycane, Mechanically Harvested

The third option for evaluation is a crop production system based on either annual harvest of sugarcane, or alternatively Type I energycane which has intermediate characteristics between traditional sugarcanes and “energycanes”. The assumed strategies would be as follows.

- Sugarcane in an annual harvest program would be farmed for efficient operation of chopper-type sugarcane harvesting equipment.
- Similarly, an energycane would be grown for chopper-type harvesting, with the crop-growth period reduced, reflecting a priority on fiber and biomass production, rather than sucrose production.
- At harvest, while all leaf trash could be forwarded to the mill with the cane, the preferred option would be for the crop to be “topped” by the harvester, such that a proportion of the green leaf and tops are left on the field as a surface mulch.
• Trash would be separated at the mill, by a pneumatic separation system. It would then be cleaned and processed prior to use.

• The cleaned sugarcane/energycane would be milled, with the separated leaf material processed separately for subsequent use.

For both sugarcane and Type I energycanes, the maximization of the sucrose component in the crop stalk will be considered important. Functionally, the primary differences in the crop production system will relate to the generally more erect characteristics of the energycanes.

The cropping strategies for both annually-harvested sugarcane and energycane would therefore be similar, with the crop-cycle length manipulated to maximize the efficiency of production of each crop.

### 3.5.1 Production System: Annual Cropping of Sugarcane

The annual cropping of sugarcane in an industry with high labor costs, such as Hawaii, embraces the inherent assumption of mechanized chopper harvesting, similar to the low cost production systems in countries such as Australia and Brazil. Such systems are based on an annual cropping system and multiple ratoon-cycles.

For the purposes of comparative analysis in this report, it is assumed that the utilization of chopper harvesting would be in parallel with a crop production system that minimized crop production costs and maximized the sustainability of the operation.

The high biomass removal with sugarcane that is associated with single-row\textsuperscript{75} harvesting equipment (where the harvester and haulage equipment traverses every row/bed) typically results in very high levels of soil compaction. The subsequent tillage programs to nominally alleviate this compaction can be anticipated to accelerate the rate of soil degradation. The degradation is both physical and biological in these production systems. This resulted in the phenomena of a yield plateau in the Australian industry after the introduction of chopper harvesting. Magarey et al.\textsuperscript{76} defined a “yield plateau” as “yield decline”, despite advances in varieties and crop agronomy which, generally, should have resulted in incremental yield increases.

\textsuperscript{75} Or bed, in dual-row cropping systems.

The Australian “Yield Decline Joint Venture” can be argued to have spearheaded very significant research programs in a number of countries. These programs have resulted in a number of strategies which are now seen as fundamental to the sustainable farming of sugarcane, while generally offering significant reductions in actual crop production costs and longer ratoon-cycle length. The four “pillars” of the Australian system, as summarized by Garside\textsuperscript{77}, are as follows:

1) Match the crop spacing/configuration with a standardized row spacing for all equipment which will enter the field, and rigorously adopt the concept of Controlled Traffic. The use of GPS guidance on equipment is considered essential.

2) Minimize tillage associated with the crop plow-out and replant processes to maximize retention of organic matter in the soil and minimize destruction of beneficial organisms in the soil. These organisms are reported to be much more susceptible to damage by tillage than plant parasitic organisms.

3) Introduce a legume fallow to break the monoculture, and change the biological balance within the soil root zone. This has the added benefit of significant capture of nitrogen, which reduces the nitrogen requirement of subsequent sugarcane crops.

4) Within practical limits, maximize the retention of crop residues on the field, particularly the residues from the tops and green leaf of the crop. Apart from the retention of organic matter in the system, this has multiple additional benefits, including:
   - Erosion control
   - Evaporation control
   - Nutrient recycling

The adoption of these principles as key parts of the farming system can be demonstrated to offer significant advantages. Halpin et al.\textsuperscript{78}, reporting on an audited analysis of the experiences of a grower group that adopted the technology, noted:


“The results clearly show that a farming system based on PCTF (Precision Controlled Traffic Farming) and the minimum tillage improved farm gross margin by 11.8% and reduced fuel usage [for combined tillage and planting operations] by 58%, compared to producers’ traditional practice. PCTF and minimum tillage provide sugar producers with a tool to manage the price cost squeeze at a time of low sugar prices.”

Experience in Australia has been that larger farming operations have often been the first to move to “New Farming Systems”, because of the significant commercial benefit, and the availability of skill sets to manage change. Loeskow et al.\textsuperscript{79} describes the impact of the adoption of the system on a family farming operation in Australia of approximately 2,500 acres in the Bundaberg region. They moved from a conventional annual harvest burnt-cane farming system with a plant-crop and approximately three ratoons, to a new system incorporating legume fallow, controlled traffic, and minimum tillage. The change included rock picking, which was undertaken on some areas of the farm. The results of the change were independently audited and the results presented to the Australian Society of Sugar Cane Technologists Conference in 2008 by Loeskow. All costs were presented in “2007 dollars”, with key points as follows.

- Land preparation costs were reduced from $1.43 per ton cane (“t.c.”) produced with the old system to $0.04 per ton of cane harvested for the new farming system incorporating controlled traffic and strategic zonal tillage. Tractor labor was reduced from $6.12 per acre ($15.12 per hectare) to $0.45 per acre ($1.12 per hectare).

- Fertilizer costs were reduced from $8.21/t.c. to $3.99/t.c., primarily as a result of the legume fallow and improved soil health.

- Irrigation application was similar for both farming systems at approximately 16 to 20 inches of applied water over the growing season to supplement rainfall. More irrigation water would typically be applied if it was available.

- Total growing costs were reduced from $24.04 to $7.33/t.c.

- At a sugar price of $300 per ton (approximately $200 per ton growers share under the Australian cane payment system), the gross margin for the farming

operation increased from - $60/acre to + $480/acre (-$147/hectare to +$1157/hectare).

Given approximate parity between the Australian-Dollar and the US-Dollar, the values can be equated.

### 3.5.2 Overview of a Potential Annual Cropping System in Hawaii

An alternative system that has potential to fit Hawaii’s environment would incorporate the latest developments in commercially proven technologies aimed at maximizing the value of all crop components while minimizing costs. Key components of the system would be as follows.

- The maintenance of the current overall cropping configuration, with the exception of a programmed move to an overall crop bed spacing of 8-feet, rather than the current bed spacing of 9-feet\(^{80}\).

- The distance between the two rows of crop on the bed would remain at 3-feet.

- The reduction in bed spacing will reduce time from planting to canopy closure, and will also increase overall plant population.

These effects will partially compensate for the reduced crop age at harvest. The configuration is illustrated in Figure 3-23.

---

\(^{80}\) The Hawaiian Industry traditionally plants its two-year cane in beds spaced at 9-foot centers with the drip tape for irrigation placed in the center of the bed.
Figure 3-23: Potential configuration of cane planting for machine harvesting in Hawaii, from commercial literature\(^81\)

Figure 3-24 illustrates a crop in Brazil planted in the desired configuration, and Figure 3-25 illustrates the harvesting operation on sloping terrain.

Figure 3-24: Crop planted in the configuration for machine harvesting with wide throat machine configuration

Figure 3-25: Harvesting a crop. The wide track undercarriage on the wide throat machine has significantly greater stability and is capable of operating in steeper fields\(^82\)

\(^{81}\) The ability to harvest this configuration may be available from other manufacturers apart from the manufacturer indicated.

\(^{82}\) Machine stability is significantly improved over standard machines because of the wider track spacing.
Key factors related to the adoption of this farming system include the following.

- The development of a crop production system based on the principles of sustainable crop production in typical Hawaiian crop spatial configuration. The system would be based on continuing utilization of GPS guidance and controlled traffic farming systems. This system utilizes the concept of permanent traffic lanes and traffic free “crop root zones”.

- The harvesters would be commercial units supplied for this row spacing configuration. Two manufacturers can potentially supply machines for this configuration. This row spacing configuration is now being rapidly adopted by a number of the largest sugar production groups in Brazil.

- For the purposes of this report, the crop age at harvest would nominally be one year; however the actual age at harvest would be manipulated to optimize crop size for the harvesters and crop-cycle considerations. For example, system optimization may be achieved with a plant-crop age slightly less than 12 months at harvest to allow nominally annual harvest, despite the time “lost” with land preparation operations at the end of the cropping cycle and if a legume fallow is incorporated.

- The crop would be harvested unburned; however every attempt would be made to utilize the topping function on the harvester to allow green leaf and tops to be left as a trash blanket in the field to maximize nutrient recycling.

- The trash extraction function on the harvester would either not be operated or operated at low speed. This results in most leaf material (which has passed through the machine) being forwarded to the mill with the billeted cane.

- The leaf material would be pneumatically extracted at the mill prior to the milling process, with clean cane being forwarded to the milling train and the separated leaf material being processes as required.

3.5.3 Crop production: Annual Cropping System in Hawaii for Sugarcane and Type I Energycane

The basis of the potential crop production system can be detailed by a chronological depiction of the field operations which would be required to introduce the system into cane lands in Hawaii. The system as described is fully commercialized by large farming operations in both Australia and other industries.
As previously noted, compatible, but not optimum, the current 9-foot bed (and drip tape) spacing would be maintained to avoid changes to the drip-irrigation infrastructure. Ideally, as fields are redeveloped, the drip spacing would be moved to 8-foot (2.44 meter) spacing. This would more accurately match the harvester and other machinery associated with the potential cropping system, and thus minimize the proportion of the field compacted by wheel traffic. It is also assumed that fields would be “run together” where practical to maximize row length for harvesting and other field operations.

The crop establishment operations assume that the introduction of the changes for machine harvesting would not initially include a legume fallow, as would be envisaged in the longer term. Installation of the cropping system would then include the following.

1) **Ripping**: Ripping areas compacted by the haulage traffic immediately after harvest, as per current practice. The “blanket” ripping operation would not be undertaken.

2) **Discing**: A single pass with heavy discs over the entire field to remove the old crop root systems, followed by a second lighter disc operation to further break down old crop root material.

3) **Field Smoothing**: Some smoothing of field surfaces will be essential because of the irregular field surface topography, both natural and as a result of current field operations. This will also include “mitering” of field edges to allow access to harvesting equipment and setup of appropriate field-edge headlands for access and end-of-row equipment turning.

4) **Mark-out and Zonal Rip**: “Mark-out” the fields and rip the permanent crop beds, utilizing high accuracy GPS. The ripping operation should be to the maximum practical depth, but be confined to a width of approximately 5 to 6 feet; with 2 to 3 feet left as undisturbed traffic lanes. The ripper should be fitted with a heavy “crumbler roller” to break down clods.

5) **Rock Removal**: After the ripping operation, rock removal would be undertaken. The rock removal strategy will be driven by the extent of rocks in the field and their distribution.

   - In fields with a limited numbers of rocks, removal is best undertaken on an “individual rock” basis, utilizing limited labor to facilitate the loading of surface rocks into trucks by a backhoe or loader.

   - The use of rock windrow equipment in association with rock pickers is an effective strategy in fields with more significant areas of surface rock.
Under field conditions with significant rock, a rock picker can be run to remove rock from the cropped bed, typically to a depth of approximately 12 inches.

- In localized areas of fields where rock removal is not practical because of the high levels of rock in the profile, rock grinding will typically be the most appropriate strategy for creating field conditions suitable for machine harvesting.

These strategies are further discussed in Section 3.5.4 Rock Removal and Management.

6) **Cane Planting:** While the configuration of the current planters, with the vehicle tracks running on the crop bed area immediately in front of the furrow openers, is highly undesirable, initially, this is the most appropriate strategy. The planters could be modified to improve “quality of job”, including the following.

- The drip tape insertion could be improved to give greater accuracy of depth control.

- Furrow openers could be narrowed and modified to allow soil to be “stockpiled” between the paired rows. Planting depth would be increased, and cover over the seedcane billets minimized to maximize the rate of emergence.

7) **Bed Reforming:** After tillering, but before the crop is too high for mechanical operations, the beds could be reformed to a profile to match the requirements of the harvester basecutters. (See profile represented in Figure 3-23.) This would be undertaken with multi-row equipment with GPS guidance.

The adoption of a legume fallow would modify the process following the rock removal operations to the following.

8) **Bed Forming:** Beds are then formed to match the requirements of the harvester basecutters. The drip tape would be placed utilizing high accuracy Real Time Kinematic ("RTK") GPS, and the legume planted.

9) **Legume Harvest or Desiccation:** If the legume is cultivar-selected for harvesting, it would be allowed to grow for its full crop-cycle. Otherwise, it will be desiccated with an appropriate herbicide after it reaches early pod-set or late-flowering.
10) **Cane Planting:** Cane planting would be undertaken utilizing planters fitted with double-disc openers to place the seedcane billets. The cane would be planted directly into the legume residues without any tillage operations. A machine designed for minimum tillage planting into three 8-foot beds simultaneously is illustrated in Figure 3-26.

![Figure 3-26: Three bed minimum tillage billet planter used in a 8-feet (2.4-m) bed system in Australia](image)

After each harvest, the crop will ratoon. Assuming sufficient residues (preferably shredded tops and green leaf) have been left by the harvesting operation, no specific tillage operations would be required, unless significant field damage has occurred during the harvesting operation. This assumes that fertilizer is applied via the drip irrigation system and other products are applied using boom-sprays or aerial application, if applicable. The use of shielded sprayers on a GPS guidance system is a cost effective method of optimizing herbicide application efficiency and effectiveness.

At the end of the crop-cycle the following takes place.

11) The maximum practical proportion of trash is taken to the mill to minimize residue left in the field.

12) The crop is irrigated and allowed to ratoon. It is then killed by the application of an appropriate herbicide, usually Glyphosate.

13) A light “bed-reforming” operation is then undertaken. This operation is used to cut out the old crop stool and reform the beds, without disturbing the drip tape.
14) The legume is planted into the beds utilizing low disturbance planter openers, and the process repeats itself.

Based on the experience of lead researcher Chris Norris in both Australia and Swaziland, with appropriate management and care, heavy duty sub-surface drip tape can be anticipated to last at least two crop-cycles of four or five years each; with three crop-cycles (a time span of 12 to 15 years) as a realistic goal. The primary factor affecting drip tape life is the loss of emitter output due to choking; primarily due to water quality and management issues.

The alternate cropping system and the traditional Hawaiian system may be compared as follows.

- Similar levels of energy and tillage costs associated with the initial installation of the system. A reduction in tillage operations would initially be offset by additional land smoothing operations.

- A requirement for rock management on a proportion of fields would be an additional cost.

- Land preparation and costs, on a per acre replanted basis, would be very significantly reduced, with total energy costs and tractor hours anticipated to be reduced to less than 50% of current levels.

- The total replant costs would be further reduced by the reduction from a two-year replant program to a five-year replant program.

- These factors could be anticipated to reduce tractor hours and energy consumption to less than 20% of traditional levels.

- Crop replant approximately every five years, instead of every two years, reduces the area required for seedcane. For instance, under the current system 1,650 acres per year are dedicated to seedcane. Under the annual cropping system only 650 acres would be required.

- The elimination of the cane washing facility would provide more land for growing cane and increase the water available for irrigation of the crop.

### 3.5.4 Rock Removal and Management

One of the pre-requisites for the successful introduction of chopper harvesters is the absence of rocks in the field, particularly in the path of the harvester basecutters. This is
critical to allow the basecutters to operate on, or marginally below, the surface of the crop bed profile. This is important both to minimize harvesting losses and to minimize damage to the crop stool. The soil around the stalk acts as an “anvil” to minimize damage to the stool during the basecutting process.

Rock removal and management would have to be integrated into a structured program if maximum acreage of land suitable for machine harvesting is to be achieved in a minimum time frame.

3.5.4.1 Rock Removal Strategies

The Mauritius industry has been a world leader in the development of strategies of rock management to facilitate machine harvesting. Key strategies adopted by the Industry have included:

- The adoption of controlled traffic and permanent traffic lanes, all based on GPS guidance
- Rock management, with a range of different approaches available for use in any field, depending on rock density and characteristics

More than one method can be used in any field. The aim is for the crop beds to be rock free, however rock at or near the surface is allowable in the permanent traffic lanes.

- The adoption of minimum tillage crop production systems, to minimize the potential for rocks in the profile being bought to the surface during subsequent field operations

Primary strategies for the management of rocks in agricultural fields are based on either:

- Rock removal
  or
- Rock pulverization in situ

The most appropriate strategy depends on a number of factors, including rock density, rock type and hardness, and the proportion of the field area affected by rock. An additional consideration is the subsequent use of the rock removed from the field.

The primary rock management strategy is to first “map” fields to allow the selection of the most appropriate strategy and prioritization of amelioration.
Rock Removal

Rock removal strategies range from “quarrying” strategies (where rocks are loosened and removed utilizing industrial quarry equipment) to removal of “floating” rock material with rock pickers. In areas with relatively low rock density, windrowing of rocks to increase the “rock density” is usually appropriate for more cost effective operation of rock removal equipment. Figure 3-27 and Figure 3-28 illustrate a rock windrower and the result of windrowing in a field in Mauritius, respectively. Windrowing is a strategy to “concentrate” the rocks for subsequent removal or pulverizing.

Rock pickers can be used to gather rocks from windrows, or to traverse the individual crop beds. While a number of designs are available, many units can be setup to drop small rocks in the traffic lanes, and carry larger rocks from the field in the machine hopper.

A heavy duty rock picker is shown in Figure 3-29. The strategy of concentrating small rocks in the permanent traffic lanes can be beneficial with respect to
traffic-ability of the field. Some manufacturers are reportedly now offering the option of a cane harvester type elevator to directly load rock into a truck running beside the picker.

Rock Pulverization

Rock pulverization can be a highly effective method of managing rock when rock density is too high for practical removal from the field. The productivity and cost of rock pulverizer machines is highly dependent on rock density and hardness. The use of this equipment is primarily justified in localized areas of fields.

![Figure 3-30: Heavy duty rock pulverizer operating in basaltic rock.](credit: www.fae.com)

Figure 3-30 illustrates a rock pulverizer typical of the type and application used in the Mauritius industry, and Figure 3-31 is a unit in operation in Mauritius. While expensive and slow for large scale operation, this system can be very useful for the management of rock outcrops. In Mauritius, a common strategy has been to utilize a 5-foot working width machine in the pre-formed beds with 6’ 3” bed centers. Surface rock can be windrowed and moved into the bed area prior to the rock grinding operation.

In a machine harvesting system based on 8-foot wheeltrack centers, a machine operating width of 6 feet would be appropriate. This reduces cost because there is no requirement for deep rock removal from the permanent wheeltrack area.

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83 The tractor requires a creeper gear to achieve the typical forward speed range of 0.2 to 0.6 miles per hour.
While “de-rocking” fields is an expensive operation, this cost can be managed. The final goal is the maximization of the number of fields suitable for mechanized harvesting at minimum cost. The most appropriate strategy to achieve this is:

- Map the fields to identify rock areas and characteristics of each of the different areas
- Develop an integrated strategy utilizing each of the potential rock removal methods, as required

“Reef” rock areas may require a combination of large rock removal and rock pulverization. Areas with “floating” smaller rocks may utilize both windrowing and rock removal.

A more detailed costing of rock removal options is beyond the scope of this report.

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84 The typical operating depth is approximately 12 inches.
3.5.5 Land Preparation and Planting Cost: Annual Cropping of Sugarcane

The assumed costs of land preparation associated with planting operations of an annual cropping system are presented in Table 3-19. These costs are based on the estimated cost of the current tillage program associated with replanting. No allowance is made for potentially very significant reductions which can be realized by the introduction of minimum tillage programs.

![Table 3-19: Assumed cost of land preparation associated with planting operations of an annual cropping system](image)

<table>
<thead>
<tr>
<th>Operation</th>
<th>$/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ripping</td>
<td>$ 67</td>
</tr>
<tr>
<td>Cross-Ripping</td>
<td>$ 61</td>
</tr>
<tr>
<td>1st Heavy Discing</td>
<td>$ 60</td>
</tr>
<tr>
<td>2nd Discing</td>
<td>$ 56</td>
</tr>
<tr>
<td>Land Smoothing</td>
<td>$ 60</td>
</tr>
<tr>
<td>Bed Forming</td>
<td>$ 25</td>
</tr>
<tr>
<td>Rock Picking</td>
<td>$ 100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$ 429</strong></td>
</tr>
</tbody>
</table>

Additional operations associated with the replant program include land smoothing, bed forming, and rock picking. The cost of the actual planting operation is assumed to be the same as the current planting cost per acre. The replant area can be defined as:

- Current area harvested for commercial cane .......... 16,350 acres
- Additional area because of reduced seedcane usage 1,000 acres
- Total area for commercial cane ....................... 33,700 acres
- Replant cycle for one-year cane ........................ 5 years
- Annual replant ........................................... 6,740 acres
The costs are summarized in Table 3-20.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost/acre</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land preparation</td>
<td>$ 429</td>
<td>$ 2,891,000</td>
</tr>
<tr>
<td>Planting</td>
<td>$ 600</td>
<td>$ 4,044,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$ 1029</strong></td>
<td><strong>$ 6,935,000</strong></td>
</tr>
</tbody>
</table>

The annual cost of land preparation and the planting operation are approximately $6.95 million.

### 3.5.6 Potential Yields: Annual Cropping of Sugarcane

In determining the productivity and potential fiber production of a machine harvested annual cropping system, it is important to derive the:

- Anticipated total fresh weight of cane and cane components under commercial crop production conditions
- Anticipated recoverable sucrose in the cane stalk at harvest after appropriate ripening strategies
- Anticipated levels of dry leaf, green leaf, and tops in ripened cane harvested annually

The following can be derived from available data sets.

1) For comparative purposes, hand-cut plot yields are typically discounted by a factor of 25% (relative to commercial yields). This takes into account both the higher yields usually achieved in small plots, and harvesting and cleaning losses. For the purposes of this report, actual crop yield is sought for comparative purposes, and a lesser “discount” to the yield is applied. 20% was selected.

After discounting yields by the nominated 20% as compensation for the data being from hand-harvested plots, the cane stalk yield for one-year cane derived in Activity 2 indicates a productivity of 3.86 t/ac/mo for two-year cane and
4.42 t/ac/mo for one-year cane. This equates to an increase of approximately 14%. Dry matter per acre per month was also higher in the one-year plots, with an increase of approximately 5%.

2) Sucrose production in the one-year cane, after the 20% discount associated with plot trials, was approximately 4% lower than the two-year cane results on the basis of tons of sugar per acre per month (t/c/ac/mo). The relationship between cane productivity and sucrose productivity are probably also influenced by natural crop maturation effects.

3) In determining levels of dry leaf, green leaf, and tops in each crop scenario, a key issue becomes the definition of “trash”. As with two-year crops, “trash” typically includes dry and sour cane. Work by Evensen\textsuperscript{85} (as reported in Activity 2) indicates that as the crop progresses from 12 months to 24 months, the biomass associated with tops is reduced by approximately 50%, and the biomass associated with trash increases. The result is similar levels of non-cane products as a percentage of total biomass. The non-cane proportions in the trials by Jakeway\textsuperscript{86} are consistent with the results by Evensen. Given the approximate doubling of cane weight over the period, this implies similar gross weights of tops for both one-year and two-year cane. This is consistent with low stalk mortality and approximately constant stalk numbers over the period. Similar comments can be argued to apply to green leaf mass prior to maturation processes commencing.

4) Dry leaf levels are somewhat more complex to estimate as a deliberate ripening program will also impact on the mass of this component. Loss of a proportion of the dry leaf can also be anticipated during the second year of the crop. For the purposes of comparative analysis, the assumption is that dry leaf levels as a proportion of total biomass will be similar for ripened one-year cane as for ripened two-year cane.

3.5.6.1 Estimated Productivity for Annual Harvest Sugarcane Crop

For the purposes of comparative analysis, the following is assumed.

- The productivity of two-year cane is assumed to be approximately 4.65 t/ac/mo in the analysis of that production option. A productivity of 4.65 t/ac/mo is also assumed for one-year cane, as a more conservative option than the 14% higher yield indicated in trials. It is also assumed, however, that a ripening program has been instituted.

- Sucrose content in one-year cane is assumed to be 5% lower than the sucrose content of two-year cane, which is similar to the observed effect in the trials.

- Levels of green leaf and tops is assumed to be of a similar mass per acre as the current two-year crop, as this is primarily driven by crop stalk population and configuration. It is also assumed that a ripening program has been utilized.

- Dry leaf fresh weight as a proportion of cane stalk net weight is assumed to be approximately 90% of the dry leaf fresh weight proportion assumed for two-year crops. This is to ensure conservative results.

A move to a cropping system that incorporates ratoon-crops also results in a reduction in yield potential, with a number of factors affecting the yields achieved.

- In Southern Africa, where hand-cutting is the predominant harvesting method, 8 to 10 ratoons are often achieved. Yield decline during the crop-cycle is in the order of 30 to 40%, indicating an annual drop in productivity in the order of 3 to 4%.

- Higher rates of ratoon yield decline are typically associated with machine harvesting. In Australia, initial ratoon-cycles were short; however ratoon-cycle length has increased. Chapman\textsuperscript{87} noted in 1988 that the average crop-cycle in 1986 was 4.3 ratoons across the fully mechanized Australian industry. Chapman noted that ratoon yield decline as a proportion of plant-crop yield was greater in lower yielding crops than in higher yielding crops. And typically, first ratoon yields are similar to the plant-crop yield, with ratoon

decline occurring after that. Average yield depression noted by Chapman in high yielding ratoons was approximately 10% per crop after the first ratoon.

- Garside (personal communication) observed that the adoption of controlled traffic farming systems has significantly reduced the rate of decline of ratoon yields relative to those noted by Chapman, and that increased ratoon productivity is a positive outcome from the adoption of this farming strategy.

For the purpose of analysis, the anticipated yields over the crop-cycle are presented in Table 3-21. The option of a legume break is not included in the analysis, although it has significant productivity benefits in spite of the “lost time”. The following is assumed.

- Crop productivity for the plant-crop and first ratoon is 4.65 t/acre/month, with monthly productivity falling by 5% for the first ratoon and 7.5% per year for later ratoons.

- The plant-crop age at harvest is 11 months, to reduce the potential for harvesting damage.

- A total crop-cycle of 58 months, to allow the standard amount of time for crop plow-out and replant operations. This is achieved by reducing the growth period of the older, lower yielding ratoons.

<table>
<thead>
<tr>
<th>Plant/Harvest (months)</th>
<th>Productivity (t/acre/month)</th>
<th>Clean Cane Yield (tons/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant-crop</td>
<td>11</td>
<td>4.65</td>
</tr>
<tr>
<td>1st Ratoon</td>
<td>12</td>
<td>4.65</td>
</tr>
<tr>
<td>2nd Ratoon</td>
<td>12</td>
<td>4.42</td>
</tr>
<tr>
<td>3rd Ratoon</td>
<td>12</td>
<td>4.09</td>
</tr>
<tr>
<td>4th Ratoon</td>
<td>11</td>
<td>3.78</td>
</tr>
<tr>
<td>Total Crop-cycle</td>
<td>58</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Note: This achieves a five-year return cycle, including a two month replant period.
Table 3-21 indicates the following typical crop yields:

- 51.2 t/ac for the plant-crop
- 55.8 t/ac for the first ratoon-crop
- 53.0 t/ac for the second ratoon
- 49.0 t/ac for the third ratoon
- 41.6 t/ac for the fourth ratoon

The total productivity will be of the order of:

- 251 t/c/acre for a five-year crop-cycle
or
- 50 t/c/acre per year over the crop-cycle

By comparison, the pre-harvest crop yield from the traditional Hawaiian cropping system would be approximately similar over the same period. The increased crop growth period of one-year cane associated with the five-year crop-cycle is effectively negated by the ratoon yield decline effect. The reduced seed area associated with ratoon cane production will increase the effective yield of the “one-year cane” option.

### 3.5.6.2 Sucrose Recovery

While assumptions for biomass produced are based on pro rata comparisons with two-year cane production systems, for the purposes of a conservative analysis of one-year cane:

- The proportion of fiber in the fresh stalk of one-year cane is assumed to be 5% lower than the fiber level in two-year cane
- POL and REFSOL in association with the fiber levels in the fresh clean stalk at harvest is assumed to result in the recoverable sucrose from clean stalk being 5% lower in ripened one-year cane than in ripened two-year cane

Based on research by Chapman, recoverable sucrose, as a percentage of harvested cane stalk, is considered to be stable across the ratoon-cycles.

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88 The two-year crop yield will be: \((5/2) \times 107 \, \text{t}_c/\text{acre} = 267 \, \text{t}_c/\text{acre} \) over a five year production period.

3.5.7 Harvesting System: Annual Cropping of Sugarcane and Energycane

3.5.7.1 Chopper Harvesting of “One-year” Cane (Process Overview)

With chopper harvesting, the crop is gathered, and billeted by the harvester in a continuous process. This involves aligning the cane stalk such that, as the harvester moves forward, the cane stalk feeds into the machine, is severed by the basecutters, and then passes along the feedtrain for presentation to the chopper system for billeting. Removal of leaf/trash material can occur immediately after the billeting operation, and again at the end of the elevator by a secondary trash extraction system.

Haulout units which operate beside the harvester then haul the billeted material to trans-loading points, where it is then transferred to transport units for transfer to the mill. If cane plus trash is being delivered to the mill, a dry (pneumatic) separation system at the mill removes the trash immediately prior to milling.

As the harvester has negligible buffer storage capacity, the harvesting operation must be well managed if the output of the harvester fleet is to be maximized. Chopper harvesters allow the crop to be harvested either burned or unburned (green). However, until developments within the last decade, the size of the crop that could be successfully harvested unburned was limited. This is because earlier machine designs were more limited in their ability to manipulate the crop to achieve successful feed than are current machines.

The crop size and the presentation of the crop have a very significant influence on the performance of all the primary functions of the harvester. In addition, harvesting of an unburned sugarcane crop has both positive and negative impacts. The primary considerations include the following:

- Impact of crop size and presentation and field conditions on harvesting losses
- Impact of crop size and presentation on harvester productivity and harvesting cost
- Impact of field layouts and parameters, such as aggregate row length, on harvester productivity
3.5.7.2 Impact of Crop Size and Presentation on Harvesting Losses

Any machine harvesting operation will have losses associated with it, with losses typically being greater in lodged crops than in crops which are erect at harvest. Many studies have been undertaken to determine the magnitude of losses associated with machine harvesting. The losses can be differentiated into “visible losses” and “invisible losses”.

- Many studies have focused on the “visible losses” associated with the chopper harvesting operation, with no attempt to measure “invisible losses”. This is primarily due to the relative difficulty in measurement; e.g., Rizo, (personal communication)\(^90\). While it is understandable that data supplied by manufacturers to quantify cane loss typically focuses only on “visible losses”, many “scientific” trials around the world have also focused solely on “visible losses” (Rozeff\(^91\)).

- In an attempt to assess both “visible losses” and “invisible losses” some research trials have used studies to compare sucrose recoveries between hand-cut operations and machine harvested operations, typically in replicated field trials; e.g., De Beer\(^92\). In his trials with two different machines, De Beer noted that estimated sucrose recovery from machine harvested replicated plots ranged between 95% and 87.5% of hand-harvested recoveries.

- Other more basic studies have correlated the relationship between crop estimates and final recovered yield with the two harvesting systems; i.e., between pre-harvested and estimated crop yield.

An alternate strategy has been to determine the source and magnitude of losses as the cane passes through the harvest process. Work done in Australia by Berding et al.\(^93\) monitored the mass balance of material as it passed through the harvester and used this data, in conjunction with the sucrose levels measured on trash (immediately after harvest), to

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determine sucrose flows. The outcome from this work was the finding that the most
significant loss was associated with the product flow out of the harvester extractor. This
included juice transferred onto trash from gathering and billeting losses, as well as the loss
associated with cane loss through the harvester extractor. The losses associated with the
extractor were the most significant.

A significant study was also undertaken in Argentina (Gomez et al.94) to compare the
absolute and relative losses during the harvesting process of burned and unburned cane by
monitoring both sucrose levels and product mass. Crop size averaged 53 t/acre for the 32
paired trials. The extractor fan speeds were deliberately very conservative relative to the
“commercial practice” monitored by Berding. Gomez noted that estimated sugar recovery
after milling was approximately 84% of the pre-harvest recoverable sucrose in the field, for
both burnt and green cane harvesting. He also noted that estimated sugar recovery after
milling was approximately 84% of the pre-harvest recoverable sucrose in the field. This
equates to losses for both burnt and green cane harvesting.

As previously noted, Burleigh95 measured losses in the recoverable sucrose in the
pre-harvest crop and the material entering the milling train in trials in Sudan. The losses
ranged from 8.7% for burnt hand-cut cane to 25.5% for burnt chopper harvested cane. It
should also be noted that due to machine design and performance considerations, as well as
the typical environmental conditions, anticipated losses would be higher in Burleigh’s trials
than would be anticipated with current harvester technology.

In addition to this work, researchers, particularly in Australia, have quantified the
losses associated with the billeting process from large scale controlled “workshop” trials96,
and the true magnitude of harvester extractor losses by both field trials97 and “workshop”

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94  Gomez, J., D. Chapple and L. McDonald. Sugar Losses in Burnt and Green Cane
Technologists. Vol. 28.
American Society of Sugarcane Technologists, 1980 Meetings, Louisiana and Florida
Divisions. pp. 29-33.
96  Hockings, P.R., C.P. Norris and R.J. Davis. Chopper Systems in Cane Harvesters: B:
Results of a Test Program. (2000). Proceedings of the Australian Society of Sugar Cane
97  Whiteing, C., C.P. Norris and D.C. Paton.  Extraneous Matter v's Cane Loss: Finding a
trials. These trials typically identified the trash extraction system as the primary source of cane loss with chopper harvesting operations in green cane.

Australian researchers have also repeatedly quantified the magnitude of losses associated with the main machine functions. From these studies, a reasonable assumption of the losses associated with the crops to be harvested in Hawaii can be derived, including:

1) Topping losses  
2) Gathering losses  
3) Basecutter losses  
4) Pickup losses  
5) Feedtrain losses  
6) Billeting losses  
7) Extraction losses

The magnitude and relativity of these losses can be further investigated, based on significant research result databases.

1) Topping Losses

Topping losses are the loss of cane stalk associated with the topping process in erect cane. Topping is highly desirable from the point of view of minimizing non-POL material entering the milling process. In lodged crops, topping is not possible. The degree of topping achieved in more erect crops is related to the evenness of the height of the cane stalk. Evenness of crop height is a significant component of variety selection for machine harvesting. Where topping efficiency is high, losses will also tend to be higher; with aggressive operational strategies, potentially approaching 5%. In lodged crops when topping is not undertaken, topping losses will, by definition, be zero.

2) Gathering Losses

These losses are predominantly in the form of damage to the cane stalk as the harvester aligns the stalks with the crop divider spirals to facilitate the feed into the machine. Gathering losses are both “visible” and “invisible”. An indication of the magnitude of the “invisible losses” can be estimated by assessing the degree of damage to the billets being produced by the harvester. The magnitude of gathering loss is also dependent upon cane characteristics, such as the brittleness that results in breakage and rupturing associated with buckling failure. Depending on the degree of lodging and other conditions, total gathering losses (“visible” and “invisible”) can range from close-to-zero to greater than 10% of the pre-harvest crop. Extremes in observed gathering losses are shown in Figure 3-32 and Figure 3-33.

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3) Basecutter Losses

Basecutter losses are usually considered to be both (1) the actual loss associate with the severing of the stalk by the harvester basecutter blades [typically considered an “invisible loss”], and (2) the “visible losses” associated with the portion of the cane stalk still attached to the cane stool after the basecutter blades have passed above ground level. The stalk losses are strongly related to both the degree of recumbancy of the crop, the basecutter height setting, and the row surface profile of the harvester. Kroes\(^{101}\) undertook fundamental research into the factors influencing basecutter losses, with an emphasis on the process of damage, although field mass loss was not quantified. Based on work at the Centro de Technologia Canavieira (“CTC”) in Brazil, Neeves\(^{102}\) notes that typically the “invisible losses” associated with the basecutting operation will range from 1.5 to 2.5%, depending on varietal characteristics and condition (sharpness) of the harvesters basecutter blades. “Visible” basecutter losses can range from close-to-zero to several percent, and are typically included with the assessment of gathering losses.

4) Pickup Losses

Pickup losses generally relate to cane which is not taken into the harvester feedtrain, because it has been severed from the stool by the basecutters or because of breakage.

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99 Very high losses and low machine productivity result.
100 High machine productivity with minimal “visible losses” result.
102 Neeves, J. CTC Brazil (personal communication with lead researcher Chris Norris).
Pickup losses are highly dependent on the degree of recumbancy of the crop, as well as breakage of cane during the gathering process. Operational practices such as using trimming saws to assist with the gathering of heavily lodged crops result in short pieces of stalk falling to the ground, a significant proportion of which can be lost.

Figure 3-32 illustrates conditions with very high “visible losses” associated with gathering, basecutting and pickup of a low yielding (of approximately 35 t/ac) crop. Figure 3-33 illustrates conditions with a high yielding, very recumbent crop (of approximately 75 t/ac) where these losses are very low.

While crops in both examples are recumbent, the even crop profile optimized to the harvester basecutters, the lack of stool tipping, and the conditions allowing the basecutters to operate on/just under the soil surface will result in the losses in the higher yielding crop being much lower than in the lower yielding crop. The use of GPS guidance facilitates a very significant reduction in losses relative to visual guidance, particularly in “dual-row” cropping configurations. This is because the GPS guidance maintains the correct alignment of the harvester relative to the planted rows.

After the gathering and feeding processes, the cane passes into the harvester and there is the potential for further losses.

5) Feedtrain Losses

Feedtrain losses are associated with some loss of cane pieces which fall through the gap between feedrollers. Again, this loss is greatest where significant amounts of broken cane or short pieces of cane are being fed through the machine. Some additional loss can occur due to physical damage to the stalk during the traversing of the feedtrain, particularly when the machine is processing a “glut” of cane. These losses are usually minimal.

6) Billeting Losses

Billeting losses occur as the blades on the chopper drums of the harvester cut through the bundle of cane stalks. Typically, with chopper blades in good condition, billeting losses are 1.8 to 2.1% per cut made in each foot of cane stalk. However, factors such as cane yield and harvester pour rate (i.e., the rate of cane stalk material flow through the harvester when operating) also impact on these losses (Hockings et al.)103. To produce a 6-inch billet, the harvester makes two cuts in each foot of cane stalk, thus billeting losses will typically be between 3.6 and 4.2%. A billet length of 9 inches results in a loss between these values. These losses are predominantly juice; however a small “wedge” of rind and

pith is also lost. As chopper blades become blunt or poorly adjusted, billeting losses increase, with very blunt and badly damaged blades increasing losses by up to 100% (Hockings et al.). “Average losses” are calculated as “sharp blade” losses plus 30%. Billeting losses are nominally 100% “invisible”.

7) Extraction Losses

Losses associated with the extraction of trash are typically the most significant losses associated with machine harvesting operations, particularly when harvesting unburned crops (Whiteing et al.; Gomez et al.). Design and space constraints mean that the efficiency of trash separation on the harvester will always be constrained, and that some cane loss will always be associated with trash removal by the harvester extraction systems. While dependent on many factors (including pour rate, cane yield, and field conditions), cane loss will generally be within the following ranges.

- 0%, when the trash extraction system is not operating, or operating at very low speed; i.e., “cane + trash” is being forwarded to the mill for separation at the mill.

- 0 to 6%, when the harvester extractor system is being operated at low fan speeds to remove a proportion of the trash (typically to modulate transport density). This strategy is typically used when additional trash separation will be undertaken before milling.

- 6 to 12%, when more aggressive settings of the extractor fans are being used to achieve “acceptable” levels of trash in the load. (This is typical of “harvesting best practice” settings.)

- 12 to 20%, when aggressive fan speed settings are being used to minimize levels of trash in the cane supply.

Extraction losses are predominantly “invisible losses”, because of the dissociation of the billets as they pass through the extractor fans, with “visible losses” typically in the order of 20% of total extractor losses (even under “workshop” conditions). The actual proportion

---


of known losses is dependent on cane characteristics and extractor fan tip speed (Whiteing et al.\textsuperscript{106}; Viator et al.\textsuperscript{107}).

In addition to the major losses associated with chopper harvesting, there are typically a number of smaller sources of loss, including “recirculating” losses and losses of billets from the elevator and spillage. These losses are all typically “visible losses”.

The “one-year cane” system just discussed (where leaf material recovery is to be maximized) will operate with either extractor fans off, or extractor fans operating at low speed. Extractor losses will therefore be eliminated or dramatically minimized.

### 3.5.7.3 Summary of Harvesting Losses

Figure 3-34 presents data on total “visible losses” and crop size from a series of trials undertaken in Colombia by Victoria et al.\textsuperscript{108} in sugarcane. The trials undertaken in large plots looked at both “visible losses” and harvester productivity in a number of different variety plots at two sites in the Cauca Valley, Colombia. Most varieties in the trial program were characteristically recumbent, with measured “visible losses” strongly associated with crop yield. Of significant interest were two more erect varieties in the trials. One, the “high loss” variety, was characteristically brittle, resulting in relatively high “visible losses”. The other was a more “tough” variety, which had lower observed losses even at high yields. The degree of lodging is strongly related to crop yield.


To determine the typical losses anticipated under Hawaiian conditions, crop characteristic assumptions are as follows:

- Crop size at harvest in the range of 42 to 56 t/acre, with an average crop size of 50 t/acre
- Crop stature similar to “typical” Hawaiian varieties with the characteristic of early lodging

For the purpose of evaluating the losses associated with chopper harvesting recumbent-type varieties of “one-year” cane with a yield in the range if 42 t/ac to 56 t/ac, the following is assumed:

- Gathering, pickup, basecutter, and feedtrain losses (front-end losses, “visible” and “invisible”) will be assumed to be 10%, and comprised of approximately equal levels of “invisible losses” and “visible losses”. It is assumed that field row profiles have been optimized for machine harvesting and all operations, including harvesting, are under GPS guidance. It is also assumed the crop has lodged heavily. These losses are higher than the losses observed by

---

Victoria et al. and may be expected to be reduced as more “harvester friendly”
varieties are introduced.

- Billeting losses, for a “benchmark” 9-inch billet, are assumed to average an
  additional 3.4% at typical harvester pour rates after allowance for “average”
  wear on the billeting blades.

- For the purposes of this analysis, where trash separation at the mill is assumed
  (and no trash separation is being undertaken on the machine), extractor losses
  are considered negligible for the one-year cane example.

While Type I energy canes are in many respects similar to current Hawaiian varieties, they
typically display more erect characteristics. This will improve harvestability.

Post-Harvest Deterioration Losses

In addition to the losses at the harvester, additional losses relate to the deterioration
of the billets between harvest and milling. This has been explored by numerous researchers,
with Saska et al.\textsuperscript{110} assessing the impact of time and temperature on losses. Key
considerations are as follows.

- With direct transport and well managed chopper harvesting, harvest-to-milling
time is normally short. This is the anticipated situation for chopper harvested
cane in a Hawaiian scenario. Further confirmation of this can be found in
published work. O’Reilly\textsuperscript{111} notes that in an operation in the Ord River in
Australia, electronic logging indicates an average harvest-to-crush time of less
than 2.5 hours for its “Just in Time” chopper harvesting operation. Based on a
basic analysis of transport unit numbers in most “24 hour Just in Time”
harvesting operations in Australia, harvest-to-mill time will typically be less
than four hours.

- With unburned cane, deterioration associated with this delay can be anticipated
to be minimal; however, some loss will occur. Based on the parameters
identified by Saska, for the one-year unburned cane at the “cut-to-crush” times
anticipated, losses associated with deterioration after harvest are calculated to
be in the order of 0.4%.

\textsuperscript{110} Saska, M., S.L. Goudeau and I. Dinu. Sucrose Loss in Storage of Green Billet Cane.

\textsuperscript{111} O’Reilly, B. Cane Supply and Transport in the Ord. Proceedings of the Australian
With burned cane, particularly at higher ambient temperatures, if harvest-to-mill time is extended, deterioration can be a factor of economic significance.

Type I energycanes will typically have similar constraints related to post-harvest deterioration of the sugar components, as in traditional sugarcane. This is because of the requirement that the recovery of sucrose be maximized.

3.5.7.4 Impact of Crop Size and Presentation on Harvester Productivity and Harvesting Cost

The primary determinant of the cost of harvesting with chopper harvesters is the productivity achieved. And the productivity achieved is in turn determined by the harvester “pour rate” and time efficiency (Ridge et al.112). Time efficiency is related to the logistical support available to the harvesting operation, as well as factors such as crop row length, headland width and condition, and associated factors (Powell113).

Harvester pour rate, or the rate of material flow through the harvester when operating, is determined by a number of factors. In low yielding crops, pour rate is limited by the forward speed capacity of the harvester; particularly tracked harvesters. The damage to the crop stool (which must be rationed) also increases with forward speed. This is a “quality of job” constraint on forward speed. As crop size increases, typical pour rates increase and forward speed reduces. As crop size increases further, the probability and degree of lodging increases and the ability of the harvester to feed the crop reduces. The harvester pour rate then reduces. This effect is more pronounced in unburned crops than in burned crops.

Figure 3-35 presents a dataset illustrating these effects developed by Ridge et al. The dataset was derived from surveys of actual harvester performance in a range of crop conditions in sugarcane. While harvester performance, particularly performance in lodged unburned crops, has improved dramatically since this data was collected, the general effect remains relevant.

The significance of this relationship is that while harvesting costs are often quoted in terms of cost per ton, the reality is that harvesting cost is best determined by hourly machine ownership and operating cost, divided by average machine throughput (Sandell and Prestwidge\textsuperscript{115}).

At the assumed “one-year cane” yield scenarios of 50 t/ac, ranging from 42 to 56 t/ac (91 to 121 t/ha), crop size generally facilitates high machine productivity, as indicated in Figure 3-35. The yield of the first ratoon-crop will result in lower machine productivity than the fourth ratoon-crop. Conversely crop sizes of 107 t/ac (230 t/ha), as assumed for the current two-year cropping system, can be anticipated to result in dramatic reductions in machine performance in burned crops and uneconomic operation in unburned crops.


As previously noted, the generally more erect nature of Type I energycanes will enhance the harvestability of these crops.

In-Field transport

Transport of cane from the harvester to the mill can be achieved by:

- “Direct transport” from field to mill, i.e., the same transport unit is utilized to collect the cane from the harvester and transport it to the mill

or

- Utilization of haulout units, to collect the cane and transfer it to a transloading zone where it is then transferred to the mill

While the “direct transport” option nominally has some capital cost benefits, the advantages of utilizing haulout units are multi-faceted, and typically result in lower overall harvesting and crop production cost.

- The use of large mill-haul units in the field will result in unconstrained compaction, which cannot be alleviated without further damage to installed drip tape. This dramatically reduces the effective life expectancy of the tape.

- The end-of-row turn time for the mill-haul units is significantly greater than a haulout unit. This significantly reduces harvester productivity (lost time).

If the very substantial benefits of controlled traffic and minimum tillage farming systems are being sought, and drip tape economic life and harvester productivity are to be maximized, the option of “direct haulage” is not viable; the utilization of haulout units becomes the “base case”.

To maximize harvest and transport system efficiency, the payload and volume of the system must be optimized to match:

1) row length
2) anticipated range in crop yield
3) anticipated load density

Assuming a yield range of 42 to 56 tons per acre and a field length of 700 feet with central end-to-end drip lines (e.g., drip lines radiating from a central feeder manifold), the clean cane yield will range from 6.2 to 8.9 tons. Ideally, the haulout should have sufficient
capacity for high yielding crops, with additional consideration for the additional trash being delivered with the cane and the final product bulk density.

Both the level of leaf material in the load and the length of the billets being produced by the harvester have a very significant impact on the load density achieved in transport units. The field-to-transloading zone, and the transloading zone-to-mill systems are affected. Load densities can generally be expected to be within predictable ranges and anticipated load densities can be derived based on parametric modeling. Assuming billet lengths in the range of 8 to 10 inches, typical load densities associated with different harvesting strategies can be broadly summarized as:

- “Burnt cane” + harvester extractor .......................... 20-24 lb/ft³
- “Clean” green cane (high extraction) ..................... 19-23 lb/ft³
- Green cane + modulated trash ........................... 17-20 lb/ft³
- Cane + dry trash (topped/untopped, low extraction) ... 15-18 lb/ft³
- “Cane + all trash” ........................................... 13-16 lb/ft³

Burned wholestalk cane will typically have a range of load densities. As noted earlier in this report, a load density of approximately 15 lb/ft³ is assumed with the current transport system with burned wholestalk cane at HC&S.

The load densities associated with green cane harvesting and trash recovery require appropriate transport strategies with respect to both the field-to-transloading zone and the transloading zone-to-mill. In both Australia and Brazil, haulout units with nominal capacities of up to 1750 ft³ are used when trash recovery is being maximized. This contrasts with units of half that volume which are typically used for burned or “cleaned green” cane. Figure 3-36 shows a high volume haulout unit supplied by a Brazilian Manufacturer. This unit has two bins, each of 800 ft³, and is capable of tipping into road transport units with a side height of over 170 inches. The units are designed for low density material and therefore are designed to minimize tare weight and machine cost.
The alternative option of “trains” of haulout units behind a tractor, as widely used in Brazil, are appropriate for very long row lengths, but inappropriate where row lengths are such that turning time significantly impacts on system productivity.

The impact of haulout unit volume on harvesting costs associated with the harvesting of “cane + trash” is significant, as the unit volume, not payload, is the primary variable affecting the cost of the operation.

Cost of Harvesting and In-field Transport

Determination of the cost of harvesting by chopper-type harvester can be derived by “first principals” analysis. However, benchmarking anticipated harvesting costs against costs for other industries can be argued to be a more appropriate strategy for this analysis. Sandell analyzed harvest payment systems in the Australian sugar industry, and quotes a range of payment methods in the report “Sustainable Biomass Supply Chain for the Mallee Woody Crop Industry”117.

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116 The volume of each of the two bins is approximately 800 ft$^3$ and the design is optimized to minimize tare weight.
An analysis of costs for “whole cane” harvesting in the Northern New South Wales industry in Australia by Sandell\textsuperscript{118} indicates total cost and a cost breakdown as shown in Table 3-22. The crop is typically a “two-year” crop, and crop size is similar to the crop size anticipated for one-year cane in Hawaii. The typical annual harvester utilization is approximately 110,000 to 130,000 tons over a 145-day harvest season. The cost is for commercial harvesting operations and payment is based on gross tonnage (cane + trash) delivered.

<table>
<thead>
<tr>
<th>Cost</th>
<th>Cane + Trash ($-Australia/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation</td>
<td>1.24</td>
</tr>
<tr>
<td>Wages</td>
<td>1.51</td>
</tr>
<tr>
<td>Fuel and oil</td>
<td>1.30</td>
</tr>
<tr>
<td>Repairs and maintenance</td>
<td>2.10</td>
</tr>
<tr>
<td>Capital ownership</td>
<td>0.76</td>
</tr>
<tr>
<td>Overheads</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.36</strong></td>
</tr>
</tbody>
</table>

While the costs presented in Table 3-22 are in Australian dollars, approximate parity can be assumed with U.S. dollars. A cost of $7.50 will be assumed as the cost per ton of product delivered to the mill. Ownership costs, including depreciation and overheads, are estimated at approximately one-third of total harvesting costs.

**Field-to-Mill Transport**

The current field-to-mill haulage units have a payload capacity in the order of 60 tons and an estimated capacity in the order of 8,000 ft\(^3\), with a nominal transport density of approximately 15 lb/ft\(^3\) in burned cane. A typical unit is shown in Figure 3-37.

To carry billeted cane, the current chain basket could be replaced with a flexible belt-type material; a strategy that has been used with success by at-least one estate in Africa. With chopper harvested cane, the ability to “peak” the loads would be reduced, and the effective capacity would correspondingly be reduced to approximately 7,000 ft\(^3\). While load densities of over 20 lb/ft\(^3\) are typical for chopper harvested burned cane, the strategy of bringing trash from the field with the cane will reduce load densities. If approximately 50 to 60\% of the trash was bought to the factory (the reminder of the trash would be retained in the field for “agronomic benefit”), load densities of the chopper harvested cane would be similar to the current load densities with wholestalk cane. The payload would therefore be

\textsuperscript{118} Sandell, G., Manager, “Harvesting Solutions” (personal communication, October 2011).
reduced in proportion to the reduced load volume, and the “round trip” cost for the current transport system is estimated at $215 per load for benchmarking purposes.

Figure 3-37: Current haulage units with a nominal capacity estimated as approximately 8,000 ft³ (based on “averaged” surcharge height) and a payload of nominally 60 tons.\(^\text{119}\)

As previously noted, cane transport costs can be determined on the basis of a “cost per trip”. The move to high volume transport units aims to mitigate the increased haulage cost associated with the transport of “cane + trash”.

It is anticipated that the most cost effective strategy for transloading zone-to-mill transport will be the modification of the current transport units for billeted cane. This would involve retro-fitting the units with either baskets for the billeted cane or a modified sling system. The effective volume, including the load surcharge, is assumed to reduce to 7,000 ft³. The cost of transport will then be related to the trip cost (currently estimated at $215 per trip for the analysis of the current harvesting system costs) and the load density of the billeted product.

\(^{119}\) With billeted cane, the effective volume will be approximately 7,250 ft³.
3.5.8 Summary of Sugarcane Harvesting Costs

Table 3-23 summarizes anticipated harvesting costs, with key assumptions as follows.

- The annual harvested area is approximately 33,700 acres\(^{120}\).

- The anticipated average cane yield will be 50 tons per acre. After accounting for anticipated trash mass and “visible” and “invisible” harvesting losses, as well as the mass associated with entrapped soil, the tonnage delivered to the mill will be approximately 51 tons per acre, for a total harvested tonnage of 1,719,000. The cost of the harvester and in-field transport is based on this tonnage.

- The cost of harvesting, assuming a per ton cost of $7.50, will be $12,892,500.

- At the anticipated harvester billet length and trash levels, the total volume of material transported to the mill will be approximately 6,800 ft\(^3\)/acre, as determined by the anticipated load density of the product being forwarded to the factory. At a per trip cost of $215 and an assumed load volume of the current transport units of 7,000 ft\(^3\), the cost of transport from the field to the mill will be $205 per acre.

<table>
<thead>
<tr>
<th>Table 3-23: Anticipated harvesting costs associated with chopper harvesting one-year cane and delivery of cane and trash to the mill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation</strong></td>
</tr>
<tr>
<td>Chopper harvesting and in-field transport</td>
</tr>
<tr>
<td>Transport to mill</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
</tr>
</tbody>
</table>

The anticipated costs associated with chopper harvesting and delivery of “cane + trash” to the mill is $19.8 million. This is a substantial increase in total harvesting costs relative to current strategies.

\(^{120}\) The annual harvest area of 33,700 acres is derived as follows. The additional 1,000 acres is due to the availability of additional harvest area because of the reduced seedcane area. 

\[ ([16,350 \text{ acres, previously harvested}) \times 2] = 32,700 \text{ acres} + 1000 \text{ acres} = 33,700 \text{ acres} \]
3.5.9 Summary of Harvesting Considerations

Key considerations in the development of a long-term strategy to move to one-year cane and machine harvesting under Hawaiian conditions include the following.

- In the longer term, it is anticipated that varieties of one-year cane with relatively erect stature will be available and harvesting losses below 10% can be anticipated. In the near term, it is assumed that losses associated with chopper harvesting would be approximately 15%, including billeting losses.

- Initially, the efficiency of the topper on the harvester would be close-to-zero due to the lodged crops. Extractor fans may be used to both modulate trash levels being forwarded to the mill and to maintain desired levels of trash cover in the fields.

- With the introduction of more erect cultivars, the efficiency of the topper mechanism would increase and the extractor system would not be used.

3.5.9.1 Trash Extraction at the Mill

As discussed in Section 3.3 for two-year cane, the traditional Hawaiian harvesting system delivers product to the mill at very low cost. The mill-based cane cleaning system results in clean product being forwarded to the shredder and milling train, and minimizes issues related to soil in the cane supplied to the milling operations. These benefits are offset by the high cost of a single-harvest crop-cycle, very high sucrose losses, and inherent problems with soil health and long-term sustainability. In addition, the current system cannot separate other crop components, such as trash, prior to the milling operation.

- A move to green cane harvesting will necessitate some modifications to the cane washing plant in order to maximize trash recovery prior to milling.

- A move to chopper harvesting would precipitate a different strategy for cane cleaning prior to milling, where the leaf material is removed pneumatically (dry trash separation).

Trash separation prior to the milling of machine harvested cane has been practiced for many decades in Cuba, primarily to reduce loses in the transport and milling process associated with high trash levels in machine harvested cane. The trash separation systems were installed at the points where the product is transloaded onto the rail system for transport to the mill. Figure 3-38 illustrates a harvester typical of the units used in Cuba. Figure 3-39 is a photograph of a typical trash separation facility at a field transport-to-rail transloading zone.
The significant development of pneumatic trash separation technology occurred in Brazil with the research organization CTC. CTC undertook very significant research and development work during the 1990s in response to mill concerns related to high trash and soil levels in machine harvested cane, and the unsuitability of billeted cane to the traditional cane washing strategy. Research at CTC resulted in systems being installed at Usina Quata, with the system being further developed and improved over subsequent years (Hassuani et al.\textsuperscript{121}). Other manufacturers and developers also began development and manufacture of systems.

The focus of the Brazilian technology has been the capability of achieving cane “cleanup”, as well as the ability to operate with both wholestalk and hand-cut cane and machine harvested billet cane. This has typically involved the use of “air curtains” across the full width of feeder tables. These systems can be argued to have relatively high energy consumption and relatively low trash extraction efficiency. Hassuani notes the performance of a system at Quata as follows:

- Trash extraction levels of up to 60%, with higher extraction efficiency achieved at higher initial trash levels
- Soil extraction from the product in the order of 70%

It should be noted that the system incorporated specific processes to maximize soil rejection.

A move to milling facilities where 100% of the cane supply is chopper harvested allows the utilization of “carrier-based” trash separation systems, as there is no longer a requirement for feeder tables or the ability to process wholestalk cane. This has led to significant developments in trash separation technology.

- The width of the air curtain is the carrier, not the width of the feeder table. The energy per unit width of the air curtain can be increased, while reducing overall energy consumption.

- The flow of product across the air curtain can be better managed to maintain an even flow and better presentation to the airflow.

“Carrier-based” trash separation systems result in separation efficiencies that are significantly higher than with “feeder table-based” systems. Energy consumption is also reduced.

Figure 3-40 illustrates a double-drop system in the Usina Costa Pinto Sugarmill in Brazil. The capacity of this system is over 1,100 tons per hour delivered cane, and trash extraction levels typically approach 90%, with negligible cane loss (Delfini, personal communication122).

Figure 3-41 illustrates an alternative design, single-drop trash separation module with a design capacity of up to 350 tons per hour incorporated into the cane carrier in a large sugar mill in Pakistan (NorrisECT.com.au). Features of this design incorporate pneumatic transfer of the trash to a remote trash recovery module. Observed results for this system design include trash extraction efficiencies greater than 80% and cane billet loss of less than 0.3%.

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Schembri et al., during testing of a prototype trash separation system in Australia, found that approximately 50% of the total mineral impurities were rejected with the trash stream; with the mineral impurities remaining with the cane product predominantly in the form of soil attached to root and stool. Similar results can be anticipated for “single-drop” systems without specific strategies for soil removal.

Based on data from early testing by CTC Brazil and the results recorded by Delfini for systems incorporating the latest technologies, along with measurements taken by lead researcher Chris Norris at “single-drop” systems in Argentina, Pakistan and Swaziland, extraction efficiencies may be assumed as shown in Table 3-24.

<table>
<thead>
<tr>
<th>Component</th>
<th>Component % Extraction/Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cane billets</td>
<td>&lt; 0.3%</td>
</tr>
<tr>
<td>Cane tops</td>
<td>5%</td>
</tr>
<tr>
<td>Green leaf</td>
<td>83%</td>
</tr>
<tr>
<td>Dry leaf</td>
<td>87%</td>
</tr>
<tr>
<td>Soil</td>
<td>50%</td>
</tr>
</tbody>
</table>

Further, based on the experience of lead research Chris Norris, the capital and operating cost of a single-drop trash separation system can be estimated at less than $0.50 per ton total product throughput, with total electrical power draw for separation and ancillary components at less than 150 kilowatts.

### 3.5.10 Product Mass Flow and Sucrose Recovery

#### 3.5.10.1 Cane Mass and Composition Resulting from Different Strategies

Table 3-25 presents a mass analysis of product flows delivered to the mill from the chopper harvesting of one-year cane.

- As for the two-year cane examples, the product delivered to the mill is the pre-harvest biomass less cane loss associated with the harvesting process. The pre-harvest biomass is assumed to be the average yield for a plant-crop and four ratoons; i.e., a five-year cropping cycle.

- The harvest losses include gathering, basecutter, and billeting losses. The soil and inorganic material incorporated by the harvesting process is included as soil and inorganic material.

- The product removed by the cleaning system is calculated as the initial component mass multiplied by the anticipated extraction efficiency of the system on that component.

- The product to mill shredder is then the product delivered to the mill facility less the product extracted by the trash separator.

The total annual tonnage of material delivered to the milling train is the tonnage per acre of the pre-harvest crop less harvesting losses and material extracted.
### Table 3-25: Component mass flow associated with chopper harvesting and pneumatic trash separation at the mill

<table>
<thead>
<tr>
<th>Pre-Harvest Crop Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>At-harvest clean cane stalk</td>
<td>50 t/ac</td>
</tr>
<tr>
<td>Total leaf and tops (fresh weight)</td>
<td>14 t/ac</td>
</tr>
<tr>
<td>Tons in field at harvest</td>
<td>64 t/ac</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product Delivered to Mill (after harvesting losses)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk</td>
<td>41.6 t/ac</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight)</td>
<td>8.1 t/ac</td>
</tr>
<tr>
<td>Soil and inorganic material</td>
<td>1.4 t/ac</td>
</tr>
<tr>
<td>Total product delivered</td>
<td>51.5 t/ac</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cleaning System: Product Removed (by mass)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk</td>
<td>0.1 t/ac</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight)</td>
<td>4.4 t/ac</td>
</tr>
<tr>
<td>Soil and inorganic material</td>
<td>0.7 t/ac</td>
</tr>
<tr>
<td>Total product removed / lost</td>
<td>5.3 t/ac</td>
</tr>
</tbody>
</table>

| Annual tonnage of leaf and tops                                     | 187,000 tons |

<table>
<thead>
<tr>
<th>Product to Mill Shredder</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane stalk</td>
<td>41.5 t/ac</td>
</tr>
<tr>
<td>Leaf and tops (fresh weight)</td>
<td>3.6 t/ac</td>
</tr>
<tr>
<td>Soil and inorganic material</td>
<td>0.7 t/ac</td>
</tr>
<tr>
<td>Total product to shredder</td>
<td>45.8 t/ac</td>
</tr>
</tbody>
</table>

| Annual Tonnage to Shredder (cleaned cane)                           | 1,696,400 tons |

The data in Table 3-25 indicates that the total annual tonnage delivered to the milling shredder will be approximately 1,696,400 tons, with an additional 187,000 fresh weight tons of leaf material which has been removed by the trash separator.

### 3.5.10.2 Product Recovery

As with the current harvest and cane washing system, final sucrose recovery is related to both mass and sucrose losses as the product moves from field to mill, as well as the product loss in the mill associated with included trash. The relatively low cane loss associated with pneumatic separation of billeted cane, along with the high trash extraction efficiency, means that milling recoveries are typically high.
An overview of the losses incurred in the harvest, transport, and washing processes with burned cane and unburned cane (with the inclusion of trash removal systems at the factory) is shown in Table 3-26. It presents the derived sucrose flow and mass losses as the product passes from the field through the washing plant and finally through the milling process.

Table 3-26 indicates that while sugar production in the field is lower with a one-year cropping system, the benefits of reduced harvesting losses dramatically outweigh this effect.

### 3.5.11 Agronomic Sustainability of Option #3: Annual Harvest Sugarcane and Energycane

The initial move to chopper harvesters in many sugar industries resulted in very significant increases in soil compaction relative to more traditional harvesting methods. The increased aggressiveness of tillage operations aimed at mitigating the soil compaction has been observed to induce a gradual reduction in measurable parameters relating to soil biological and physical health.

Research, spearheaded in Australia but since replicated in many other industries developed crop production concepts which dramatically enhanced the agronomic and environmental sustainability of sugarcane production in association with machine harvesting. These developments are generally referred to under the umbrella of “New Farming Systems”. Cornerstones of this system include the adoption of controlled traffic, minimum tillage, legume fallow, and organic matter retention.

More recently, the potential to utilize sugarcane trash as an energy source has increased the rate of adoption of chopper harvesting in many industries. While this inherently reduces the levels of organic matter retention achieved, the basic components of a sustainable and cost effective crop production system are retained.

### 3.5.12 Option #3 Summary: One-year Sugarcane and Type I Energycanes

The development of strategies for the annual harvest of sugarcane and Type I energycane involves the use of chopper harvesters. This is a very significant change, and includes the following.

- Major changes to current agricultural production methods, including the move to annual or quasi-annual cropping. This would involve significant changes to all aspects of crop management.
Table 3-26: Product mass flow and recoverable sucrose flow from the field through the cleaning and milling processes

<table>
<thead>
<tr>
<th></th>
<th>Burnt Cane Washed</th>
<th>Green Cane Washed</th>
<th>Wash + Olsen</th>
<th>1-year Cane Chopper Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cane in Field Prior to Harvest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoverable sucrose in stalk (%)</td>
<td>16.4%</td>
<td>16.9%</td>
<td>16.9%</td>
<td>16.05%</td>
</tr>
<tr>
<td>Tons clean stalk/acre</td>
<td>107</td>
<td>107</td>
<td>107</td>
<td>50</td>
</tr>
<tr>
<td>Tons recoverable sugar (t/acre)</td>
<td>17.54</td>
<td>18.08</td>
<td>18.08</td>
<td>8.05</td>
</tr>
<tr>
<td>Sucrose at Delivery for Pre-cleaning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoverable sucrose in clean stalk</td>
<td>16.2%</td>
<td>16.8%</td>
<td>16.8%</td>
<td>16.05%</td>
</tr>
<tr>
<td>Tons stalk/acre</td>
<td>97.4</td>
<td>97.4</td>
<td>97.4</td>
<td>42.6</td>
</tr>
<tr>
<td>Tons sugar/acre</td>
<td>15.8</td>
<td>16.4</td>
<td>16.4</td>
<td>6.83</td>
</tr>
<tr>
<td>Sugar Recovered in Mill</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tons sugar / acre recovered</td>
<td>12.2</td>
<td>11.2</td>
<td>11.6</td>
<td>6.62</td>
</tr>
<tr>
<td>Sugar losses: Field to milling train</td>
<td>29%</td>
<td>29%</td>
<td>31%</td>
<td>15%</td>
</tr>
<tr>
<td>Factory sugar losses: Sugar lost between entering milling train and final recovery</td>
<td>2%</td>
<td>13%</td>
<td>7%</td>
<td>3%</td>
</tr>
<tr>
<td>Field and factory loss of recoverable sugar</td>
<td>33%</td>
<td>38%</td>
<td>36%</td>
<td>18%</td>
</tr>
<tr>
<td>Total sugar recovery (tons/year)</td>
<td>199,874</td>
<td>182,799</td>
<td>190,377</td>
<td>229,709</td>
</tr>
<tr>
<td>Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber in cane entering milling train (%)</td>
<td>15.4%</td>
<td>22.1%</td>
<td>18.2%</td>
<td>16.3%</td>
</tr>
<tr>
<td>Fiber in bagasse (t/acre)</td>
<td>14.05</td>
<td>20.2</td>
<td>16.12</td>
<td>6.91</td>
</tr>
<tr>
<td>Fiber from Olsen Rolls (t/acre)</td>
<td>5.9</td>
<td>4.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fiber recovered (t/acre)</td>
<td>14.05</td>
<td>20.19</td>
<td>22.01</td>
<td>10.98</td>
</tr>
<tr>
<td>Total fiber recovery (tons)</td>
<td>229,740</td>
<td>330,040</td>
<td>359,800</td>
<td>370,100</td>
</tr>
<tr>
<td>Milling Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acres/hr for mill @ 50t/hr Fiber</td>
<td>3.6</td>
<td>2.5</td>
<td>3.1</td>
<td>7.23</td>
</tr>
<tr>
<td>Harvest length @ 80% time efficiency</td>
<td>236</td>
<td>341</td>
<td>275</td>
<td>243</td>
</tr>
</tbody>
</table>

124 The tons sugar/acre at delivery is the pre-harvest tons sugar/acre less direct and indirect harvesting losses.
The requirement for significant smoothing of fields and removal of rocks. The most viable strategy would be the adoption of farming systems based on the concept of controlled traffic and minimum tillage to “manage” the rock problem after the initial rock removal programs.

Despite these issues, the move to minimum tillage in conjunction with the typical ratoon-cycles associated with annual cropping would result in a reduction in tillage cost per ton cane to approximately 20% of current levels and a reduction in planting costs to 30 to 40% of current levels.

An additional benefit would be an increase in the amount of land available for commercial production, as the area currently used for seedcane will be substantially reduced.

The cost of chopper harvesting will be substantially higher than the cost of the current harvesting system, with the annual cost of the different harvest and transport operations estimated as follows.

- Current system ......................... $11,610,000/year
- Current with green cane ............. $17,389,000/year
- Chopper harvest one-year cane .... $19,811,000/year

Against this increase in the cost of the harvesting operation is a predicted substantial increase in sugar recovery relative to the current burned cane and potential green cane harvesting options. Table 3-27 presents a summary of the anticipated sucrose recovery and fiber recovery of the “one-year” chopper harvested cane option against the current burned cane and potential green cane production systems. The reduction in losses at the mill associated with the chopper harvesting option (relative to the current harvesting strategies) is the primary driver for the very significant increase in sucrose recovery.

A significant additional benefit of a move to chopper harvesting and dry trash separation at the mill is the elimination of both the direct cost of the current cane cleaning plant and the loss of productivity associated with the area required for water and waste disposal.
### Table 3-27: Product mass flow and recoverable sucrose flow from the field through the cleaning and milling processes

<table>
<thead>
<tr>
<th></th>
<th>Burnt Cane Washed</th>
<th>Green Cane Washed</th>
<th>Green Cane Wash + Olsen</th>
<th>1-Year Cane Chopper Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sugar Recovered in Mill</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tons sugar / acre recovered</td>
<td>12.2</td>
<td>11.2</td>
<td>11.6</td>
<td>6.62</td>
</tr>
<tr>
<td>Loss of recoverable sugar</td>
<td>33%</td>
<td>38%</td>
<td>36%</td>
<td>18%</td>
</tr>
<tr>
<td>Total sugar recovery (tons/year)</td>
<td>199,874</td>
<td>182,799</td>
<td>190,377</td>
<td>229,709</td>
</tr>
<tr>
<td><strong>Fiber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber in bagasse (t/acre)</td>
<td>14.05</td>
<td>20.2</td>
<td>16.12</td>
<td>6.91</td>
</tr>
<tr>
<td>Fiber from Olsen Rolls/dry cleaner (t/acre)</td>
<td>5.9</td>
<td>4.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fiber recovered (t/acre)</td>
<td>14.05</td>
<td>20.19</td>
<td>22.01</td>
<td>10.98</td>
</tr>
<tr>
<td>Total fiber recovery (tons)</td>
<td>229,740</td>
<td>330,040</td>
<td>359,800</td>
<td>370,100</td>
</tr>
</tbody>
</table>

#### 3.6 Crop Option #4: Type II Energycane and Energy Grasses (including Banagrass), Mechanically Harvested on an Annual or Shorter Basis

Both banagrass and Type II energycane appear on the Short List of crops for biomass production at HC&S that was developed in Activity 2. The Activity 2 report notes that Type II energycane is a class of hybrid sugarcanes with attributes of low levels of sugar production and very high levels of fiber production. Banagrass is a cultivar of elephantgrass (*Pennisetum purpureum*), a tropical grass species native to Africa and introduced to Hawaii from Australia by HSPA in the 1970s. Banagrass is well adapted to tropical and near tropical environments, and is broadly representative of energy grasses. It is currently used for forage, biomass and orchard windbreaks.

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125 [http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm](http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm) (Accessed: Mar 2013)


127 The banagrass most familiar in Hawaii is not a hybrid of elephantgrass and pearl millet, as often reported in the literature; although hybrids of banagrass and pearl millet have been produced in Hawaii by the Natural Resources Conservation Service (“NRCS”) at its Plant Material Center, and are maintained in plots on Molokai.
El Bassam\textsuperscript{128} refers to banagrass as one of the “tall grasses”. He notes:

“The tall grasses have high biomass yields because of their linear crop growth rates over long periods of 140–196 days, and sometimes even longer. They can yield oven dry biomass of 20–45 t/ha in colder subtropical or warmer temperate zones, and over 60 t/ha annually in Florida. Grasses as bioenergy crops can be used as feedstocks for industrial processes or burned directly to produce energy.”

El Bassam also notes that:

“Grass tribes may be grouped into panicoid grasses and festacoid grasses. The panicoid group contains most of the African grasses and fixes carbon via the C\textsubscript{4} pathway. Their optimum temperature is 30–40°C and optimum light intensity is 50–60 klux. Panicoid grasses can fix 30–50 g/m\textsuperscript{2}/day of dry matter.”

He also notes that:

“…their high biomass yields make them interesting subjects for energy production (Burton, 1993). Desirable characteristics for energy feedstocks include efficient conversion of sunlight, efficient water-use, capture of sunlight for as much of the growing season as possible, and low external inputs.”

In further comment, El Bassam notes:

“The grass is usually propagated vegetatively. A good supply of nitrogen is required for high yields (Duke, 1983). The grass is established from stem cuttings or crown divisions. If cut once a year, \textit{P. purpureum} can produce more dry matter per unit area than any other crop that can be grown in the deep south of the USA (Burton, 1993). It is one of the highest-yielding tropical forage grasses. The annual productivity ranges from 2 to 85 t/ha. An investigation by Miyagi (1980)

yielded 500 t/ha wet matter (70 t/ha DM), spacing the plants 50 cm × 50 cm.”

The high yield potential of banagrass is also noted by a number of commentators. Duke\(^{129}\) notes:

“According to the phytomass files (Duke, 1981b), annual productivity ranges from 2 to 85 MT/ha. Miyagi (1980) obtained annual yields as high as 500 MT WM/ha and 70 MT DM, spacing the plants 50 x 50 cm, outdoing the high reported by Bogdan (1977) at 310 MT WM. Some of the higher DM yields reported are 19 MT/ha in Australia, 66 in Brazil, 58 in Costa Rica, 85 in El Salvador, 48 in Kenya, 14 in Malawi, 64 in Pakistan, 84 in Puerto Rico, 76 in Thailand, and 30 in Uganda (Duke, 1981b). Stems of elephant grass are primarily lignocellulose with virtually no juice sugars. High N is required for high biomass yields. Experimental yields in Queensland, Australia, have attained 70 MT DM/ha/yr of which 50 are stem. Expected farm yields might be 50–55 MT DM, while the best sugarcane yields are about 50 in north Queensland. Stewart et al. (1979) identified no other advantage of elephant grass over sugarcane as an energy crop. *Pennisetum americanum* is reported to yield 1–22 MT/ha/yr, *P. clandestinum* 2–25, *P. pedicellatum* 3–8, *P. polystachyion* 3–10 (Duke, 1981b).”

Extensive research has been undertaken on banagrass dry matter yield in Hawaii, as reported in Activity 2.

### 3.6.1 Production Strategies: Energy Grasses

The long-term sustainable production of energy grasses, such as banagrass, will involve principles similar to those required for the sustainable production of sugarcane. As with sugarcane, sustainability of long-term yields can be expected to be maximized by the utilization of a legume break at the time of replanting to break the monoculture. The farming system will then follow the principals evolved for “New Farming Systems” for sugarcane, as discussed earlier in Section 3.5.1 Production System: Annual Cropping of Sugarcane.

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As discussed later in Section 3.6.3 [Harvesting Systems: Energy Grasses (including Banagrass)] of this report, the preferred option for the harvest of banagrass will be high productivity forage harvester equipment. The crop configuration would be designed for efficient operation of forage harvester type equipment. Key considerations would include the following:

- Crop bed spacing
- Crop configuration on the bed
- Land preparation strategies
- Planting
- Post-planting operations
- Crop rejuvenation / replant strategies
- Potential drip tape life

### 3.6.1.1 Crop Bed Spacing

The crop would be grown in a bed cropping system similar to that described earlier for annually harvested sugarcane and energycanes in Section 3.5 (Option #3: One-year Sugarcane and Type I Energycane, Mechanically Harvested”); i.e., a bed cropping system with the bed spacing matched to suit the wheel spacing of high capacity forage harvesters. This is nominally 8 to 9 feet, and similar to the current HC&S sugarcane production system. The forage harvester would be optioned to the same wheel spacing as the sugarcane production system.

The matching of crop bed spacing with equipment spacing is considered essential to achieve “controlled traffic”, because of the high levels of biomass transport associated with the harvesting system.

### 3.6.1.2 Crop Configuration

In banagrass biomass yield trials, Duke and others refer to a crop spacing configuration of 20-by-20-inches (50-by-50-cm), and note very high yields associated with this spacing configuration. Anon\(^{130}\) notes that banagrass is

> “Normally planted in rows 0.5-2 m apart, and 0.3-1 m apart within rows. Close spacing is required for soil conservation contour hedgerows and for high rainfall environments. More open spacing is used in drier environments.”

\(^{130}\) [http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm](http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm) (Accessed: Feb 2010)
Under the cropping system anticipated at HC&S for banagrass, irrigation would be by buried drip tube. There is no practical method to achieve the 20-by-20-inch crop spacing with drip irrigation, unless a drip tape spacing of 40 inches is used instead of the current 108 inches. This is not a commercially viable option. It is assumed that an HC&S crop would be grown on a system of 9-foot beds, with a single drip tape buried in the center of each bed.

Nominally, a crop configuration of four rows on the crop bed (at a nominal spacing of 1 foot 9 inches on the bed) could be utilized. This has the advantage of approximating the 20-by-20-inch spacing in trials quoted by Duke and others. The four-row system potentially provides rapid canopy cover, with higher initial interception of radiation than wider spacings. This could nominally maximize yield potential.

In reality, this configuration, with the drip tube located in the center of the bed, would result in the inner two rows accessing most of the applied irrigation water and the outer rows on the bed being potentially water stressed. The eventual effect would be a “single wide row” across the drip tape.

Banagrass trials undertaken in Hawaii have been established utilizing a two-row system replicating the sugarcane spacing. While the wide spacing will clearly result in some loss of yield potential in a regularly harvested cropping system, it would allow sugarcane production equipment to be utilized for most crop production operations.

### 3.6.1.3 Land Preparation Strategies

The crop production system for energy grasses would replicate the operations discussed earlier for one-year sugarcane.

- The haul roads associated with the last cane harvest would be ripped to initiate the “repair” process necessitated by the extreme, localized compaction associated with the cane haulage operation.

- The field would be disc'd with heavy offset disc harrows, and land smoothing operations would be undertaken to establish a field surface suitable for crop harvesting equipment that will operated along the crop beds.

- Depending on the prevalence of rock, the fields would be ripped along the alignment of the intended crop beds and drip tape.

- Surface rock removal would be undertaken.
3.6.1.4 Planting

Anon\textsuperscript{131} notes that banagrass is

“…almost invariably planted from setts or cuttings (pieces of cane) or splits (rooted pieces of clump). Setts are taken from the basal 2/3 of moderately mature stems and should contain at least 3 nodes. These are pushed into the soil at 45°, basal end down, with 2 nodes buried. Cuttings can also be planted horizontally into a furrow, to a depth of 5-10 cm.”

It is anticipated that at HC&S, banagrass would be planted utilizing current sugarcane planting equipment. Key assumptions are as follows.

- It is anticipated that the banagrass seed pieces would be harvested with a cane harvester, as has been done previously.

- Stalk weight of sugarcane suitable for planting will typically be in the order of 2.5 to 4 lb/ft. Given the lower typical diameter, banagrass could be anticipated to be in the range of 1 to 2 lb/ft. To meet the anticipated emerged plant spacing requirements of a nominally continuous line of planted seed pieces, a planting rate of approximately half that used for sugarcane would be required.

- To achieve this, both flight size on the metering belts and belt speed would have to be modified on the billet planters.

3.6.1.5 Post-planting Operations

As with sugarcane, post-crop emergence operations of “bed smoothing” and removal of surface rock (to facilitate eventual harvest operations) are required. Additional post-planting operations include nutrition and weed control.

\textsuperscript{131} \url{http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm} (Accessed: Feb 2010)
Nutrition

Anon\textsuperscript{132} notes:

“(Banagrass) should be planted into fertile soil. Once established, requires, 150-300 kg/ha/yr N, together with other nutrients as indicated by soil tests. Responses at much higher levels of applied N have been obtained. Yields decline rapidly if fertility is not maintained.”

Fertilizer programs, including application of fertilizer by fertigation, would be similar to the strategies utilized for sugarcane.

Weed Control

Given the aggressive nature of crops such as banagrass, once good initial crop establishment is achieved, weed control should be minimal. To the extent herbicides are required; application would be achieved utilizing boomsprays, with GPS guidance.

3.6.1.6 Crop Rejuvenation / Replant Strategies

After each harvest, specific heavy tillage operations are not required unless there was significant damage to beds that must be repaired. At the end of the crop-cycle, the following strategies would be implemented.

1) The crop is irrigated to encourage ratoon growth and the regrowth killed by the application of a non-selective herbicide.

2) A light “bed-reforming” operation is undertaken to trim the beds and rip under the crop row, without disturbing the drip tape.

3) Ideally, a legume is planted into the beds. Sunnhemp or other high biomass legume crops may be appropriate as they could then be utilized as biomass at the industrial facility.

4) After harvest/desiccation of the legume, the banagrass is replanted. The option of utilizing “zero tillage” strategies to replant the banagrass would appear to be the most obvious strategy.

\textsuperscript{132} http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm (Accessed: Feb 2010)
3.6.1.7 Potential Drip Tape Life

As has been noted in earlier sections of this report, with appropriate maintenance, including avoidance of traffic on the crop beds, drip tape life expectancy would be at least two and potentially three banagrass crop-cycles.

3.6.1.8 Crop Establishment Costs

The costs associated with the production of energy grasses will be highly dependent on the anticipated crop-cycle length. Assuming at least a six-year replant cycle, approximate costs can be estimated as follows.

- Land preparation costs for the initial planting (using production methods for sugarcane) will be similar to current costs, on a per-acre basis. The annualized costs can be expected to be approximately one-third of the costs for sugarcane, because of the six-year, rather than two-year, crop-cycle.

- While land preparation costs after the initial crop establishment will be approximately 50% of the costs associated with the first crop-cycle, this is not considered in this analysis.

- The planting rate anticipated is approximately 50% of the planting rate for sugarcane. Seed material supply costs can be assumed to be similar, on a per-ton basis. The actual planting operation will be similar to current practice.

- Drip tape costs will be similar to current practice, but are not considered in this analysis.

For the purpose of analysis, it is assumed that the entire cropped area is planted to banagrass or energycane, and that the crop-cycle will be six years.

- Total area available for crop less seed area … 33,700 acres
- Replant cycle …………………………………… 7 years
- Annual replant ………………………………… 4,800 acres

The planting rate is approximately 50% of the planting rate for cane, and the revised cost of the planting operation is assumed as $400/acre. The costs are summarized in Table 3-28.
Table 3-28: Cost of land preparation and the planting operation for energy grasses

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost/acre</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land preparation</td>
<td>$ 429</td>
<td>$ 2,089,000</td>
</tr>
<tr>
<td>Planting</td>
<td>$ 400</td>
<td>$ 1,920,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$ 1029</strong></td>
<td><strong>$ 4,009,000</strong></td>
</tr>
</tbody>
</table>

The annual cost of land preparation and the planting operation is approximately $4,009,000.

### 3.6.2 Yield and Harvest Frequency: Energy Grasses

Key assumptions related to the production of energy grasses are as follows.

- The primary product of these crops is fiber. El Bassam notes that the “tall grasses” have higher levels of hemi-cellulose than crops such as sugarcane.

- Were juice extracted from the energy grasses, there would be no usable sugars of consequence in the juice.

- Moisture content at harvest can be as high as 70 to 75% in the plant-crop, with some indications that the moisture content in the ratoon-crop will be lower. It is anticipated (Osgood, personal communication) that moisture content at harvest may be somewhat modulated by pre-harvest irrigation strategies.

“Energy grasses” typically have aggressive regrowth characteristics after harvest and a large number of ratoon-cycles can be achieved if properly managed. Potential yields of banagrass, both plant-crops and ratoon-crops, are discussed in Activity 2. It includes data from a trial at the Plant Materials Center on Molokai, as presented in Table 3-29 below. The Molokai trials indicate:

- Average dry matter yields of approximately 12 tons per acre on an average harvest period of 7.54 months; a productivity of 1.59 tons of dry matter per acre per month

- Significant variability in growth-rate depending on time of year, with a spring-summer growth-rate of 2.58 tons of dry matter per acre per month, and a fall/winter growth-rate of 1.19 tons of dry matter per acre per month
Since there is no requirement to target specific maturity aspects of an energy grass crop, there is significant flexibility in the timing of harvests. However, harvesting capacity must still nominally match the crop production rate to avoid excessive crop size at harvest.

<table>
<thead>
<tr>
<th>Crop cycle</th>
<th>Crop Age (mo)</th>
<th>Harvest Date</th>
<th>Dry Matter Yield (t/ac)</th>
<th>Dry Matter (t/ac/mo)</th>
<th>Dry Matter (t/ac/yr)</th>
<th>Growth Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>7.23</td>
<td>4/20/87</td>
<td>6.87</td>
<td>0.94</td>
<td>11.29</td>
<td>Fall/Winter</td>
</tr>
<tr>
<td>First Ratoon</td>
<td>7.06</td>
<td>11/8/87</td>
<td>15.80</td>
<td>2.24</td>
<td>26.85</td>
<td>Fall/Summer</td>
</tr>
<tr>
<td>Second Ratoon</td>
<td>6.26</td>
<td>5/24/88</td>
<td>9.69</td>
<td>1.55</td>
<td>18.57</td>
<td>Summer/Winter</td>
</tr>
<tr>
<td>Third Ratoon</td>
<td>9.63</td>
<td>2/22/89</td>
<td>15.83</td>
<td>1.64</td>
<td>19.72</td>
<td>Fall/Winter</td>
</tr>
<tr>
<td>Fourth Ratoon</td>
<td>5.86</td>
<td>8/23/89</td>
<td>15.10</td>
<td>2.58</td>
<td>30.92</td>
<td>Spring/Summer</td>
</tr>
<tr>
<td>Fifth Ratoon</td>
<td>7.43</td>
<td>4/3/90</td>
<td>8.87</td>
<td>1.19</td>
<td>14.32</td>
<td>Fall/Winter</td>
</tr>
<tr>
<td>Sixth Ratoon</td>
<td>9.33</td>
<td>1/8/91</td>
<td>11.61</td>
<td>1.24</td>
<td>14.93</td>
<td>Summer/winter</td>
</tr>
<tr>
<td>Totals</td>
<td>52.80</td>
<td>NA</td>
<td>88.77</td>
<td>1.68 (average)</td>
<td>20.17 (average)</td>
<td>NA</td>
</tr>
</tbody>
</table>

TDMAM= tons dry matter per acre per month
Source: Osgood and Dudley (1993)
Note: This table also appears as Table 2-43 in Activity 2.

Other trials conducted at HC&S reported plant-crop productivities of 1.42 tons of dry matter per acre per month over a 7.1-month cycle and first ratoon of 3.47 tons of dry matter per acre per month over a 9-month growth cycle. (See Activity 2.) This equated to dry matter productivity of 31 tons per acre. When a 25% experimental discount (as used in Activity 2) is applied, this amounts to 23.25 tons per acre per year.

For the purpose of analysis of the harvesting process, it is assumed that the crop will be harvested on an annual cycle, with the following parameters.
- Average productivity of plant- and ratoon-crops across all seasons will be 1.65 tons of dry matter per acre per month; for an annual dry matter yield of 19.8 tons per acre per year.

- Assuming an average moisture content of 65%, the fresh weight biomass accumulation will average 5.2 tons per acre per month.

- Annual fresh weight yield will be 62.5 tons, fresh weight per acre.

- Peak dry matter productivity will be 3.0 tons of dry matter per acre per month, with a moisture content of 68%; for a peak fresh weight biomass accumulation of 8.6 tons per acre per month. The typical average yield can potentially be achieved in 7.2 months; however this would be followed by reduced growth rates.

### 3.6.3 Harvesting Systems: Energy Grasses (including Banagrass)

Research undertaken in Hawaii\(^\text{133}\) utilized sugarcane chopper harvesters (Claas type) for harvesting banagrass. This strategy apparently worked well on a trial basis. Table 3-30, reproduces data in Activity 2’s Table 2-45; data from harvesting trials of banagrass at Molokai.

| Table 3-30: Mechanical harvesting results for Molokai banagrass test |
|-------------------------------------------------|------------------------|
| Harvester Productivity Adjusted for Time Waiting for Haulers | 0.65 ac/hr |
| Average Particle Length                                  | 11.3 inches |
| Bulk Density of Biomass                                   | 7 to 8 lb/cubic foot |
| Recovery of Biomass                                       | 73 % |
| Harvest Rate                                              | 27 tons/hr |
| Source: Osgood et al. (1996)                              |
| Note: This table also appears as Table 2-45 in Activity 2. |

Despite the potential benefit of being able to utilize sugarcane harvesting equipment (from a machine utilization viewpoint), this is not the preferred option for harvesting banagrass. Key considerations include:

- Crop base-cutting system
- Billet length and load density
- Separation of product components on the harvester
- Machine productivity
- Machine stability and functionality in anticipated conditions
- Capital cost versus machine capacity

### 3.6.3.1 Base-cutting System

By design, there are significant differences in the systems used by sugarcane harvesters and forage harvesters as the product is severed from the root system in the harvesting process.

- Sugarcane is relatively brittle, and is usually cut at or below ground level to maximize sucrose recovery.

- Anon\textsuperscript{134} notes that the optimum height of cut of banagrass will typically be 6 inches (150 mm). For effective operation at the low tip speeds used, sugarcane harvesters typically operate the basecutters just below ground level, such that the soil acts as an “anvil” to protect the stool from damage. Banagrass stalk diameters are generally smaller than that encountered with sugarcane; typically less than 1¼ inches (30 mm) (Anon). This makes the stalk more difficult to sever.

- Fiber levels for banagrass are significantly higher than for sugarcane. Kroes\textsuperscript{135} noted that as fiber levels in sugarcane increased, the minimum impact speed of the basecutter blades had to increase to achieve a clean cut. At the high fiber levels anticipated for banagrass (typically approaching 30%\textsuperscript{136}) the rotational speeds of the basecutters on a sugarcane harvester can be anticipated to cause some damage and uprooting of the stool. The significantly higher tip speeds

\textsuperscript{134} http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm (Accessed: Feb 2010)


\textsuperscript{136} See Activity 2 of the Biofuels Assessment.
Biofuels Assessment
(Project No. 660079)  Activity 3 - Production, Harvesting and Handling Assessment

associated with forage harvester cutting systems (not designed to be in contact with the soil) can be seen as advantageous.

- The preferred field conditions (where banagrass would be grown) would be areas that are sub-optimal for sugarcane. Typically, this would be in fields with a higher level of rockiness. Harvest strategies wherein the crop is cut above ground levels, in association with surface rock management, will be essential.

For banagrass, the system utilized on forage harvesters is more appropriate than the systems designed for sugarcane harvesters.

3.6.3.2 Billet Length and Load Density

Depending on the options selected, modern sugarcane harvesters can be setup to cut billet lengths ranging from approximately 6 inches to approximately 14 inches. The Claas units used in the Molokai trials would cut a nominal billet length of approximately 12 inches under typical operating conditions, with the “end billets” on each stalk reducing the average length for the trial to the reported 11.3 inches.

This billet length resulted in a nominal load density of approximately 7 to 8 lb/ft³. This load density is less than half that anticipated for sugarcane, and is a function of the:

- thin stalk diameter and long billet length (Vitale and Domanti\textsuperscript{137})
- proportion of leaf material in the load

The following is for comparative purposes.

- Assuming a 70\% aggregate moisture content of the harvested product, the load density achieved is in the order of 2 to 2.5 lb/ft³ of dry fiber.
- This is nominally around half of what is typically achieved with corn forage, which is typically approximately 5 lb/ft³ on a dry fiber basis, or approximately 14 lb/ft³ on a wet basis.

• Observations relating to the fresh weight load density of sweet sorghum by Webster et al.\textsuperscript{138} indicated:
  
  o Forage harvested sweet sorghum had a load density of greater than 25 lb/ft\textsuperscript{3}
  
  o Sugarcane (normal green cane harvesting with trash extraction) had a load density of approximately 20 lb/ft\textsuperscript{3}
  
  o Sweet sorghum, harvested with “fans on; cane harvester”, had a load density of approximately 12.6 lb/ft\textsuperscript{3}
  
  o Sweet sorghum, harvested with “fans off; cane harvester”, had a load density of approximately 11.3 lb/ft\textsuperscript{3}

• The load density of forage harvested “whole crop” (crop including all leaf material) was over twice the load density of product harvested as “whole crop” by the sugarcane harvester.

In the absence of specific requirements for long billets, minimizing particle length maximizes load densities. A load density for forage harvested banagrass is assumed as 20 lb/ft\textsuperscript{3}. Additionally, forage harvested product will be more easily handled at the factory.

3.6.3.3 Separation of product components on harvester;

Duke\textsuperscript{139} notes that in 70 tons of dry matter (“t\textsubscript{dm}”) per hectare crops in Australia, the stem contributed approximately 70\% of the fiber. While this is a significantly higher proportion than typically observed for sugarcane (where leaf material contributes approximately 50\% of the total fiber), the fiber levels of the banagrass stalk are approaching 100\% higher than for sugarcane. The harvesting system used may have some ability to manipulate the recovery of crop components. For example, a sugarcane harvester has the capacity to:

• Remove the tops off erect plants as the first step in the harvest process

• Further extract leaf and light material after the billeting process


In sugarcane harvesting, where the goal is to minimize the amount of leaf and other extraneous material being forwarded with the cane to the mill, these are essential functions. Harvesting with forage harvesters results in all product being recovered and processed. With the harvesting of banagrass, the ability to remove a portion of the leaf fraction may or may not be advantageous.

- As noted by Duke, leaf material is a lower percentage of the total biomass dry matter than for sugarcane.
- The stalk is high in moisture content, with the aggregate moisture content of both green and dry leaf probably lower than the moisture content of the stalk. There is no advantage in removing leaf material from an energy recovery viewpoint.
- While leaf material will have an impact on load density, the value of the material (with respect to fiber content) makes separation generally undesirable.
- In the trials by Webster et al., removal of leaf material had relatively little impact on load densities.

3.6.3.4 Machine productivity

Sugarcane Harvester

A sugarcane harvester, by design, harvests a single “bed” of product. In the envisaged cropping system, this is an 8-foot bed. Harvester forward speed is limited to approximately 5 miles per hour because of operational constraints on the basecutters. In a 62.5 ton per acre fresh weight crop, this equates to a pour rate of approximately 303 tons per hour. Based on experience with “whole of crop” sugarcane harvesting, constraints on elevator volumetric capacity when delivering “whole crop” banagrass can be anticipated to limit the harvesting rate to approximately a 150 tons per hour pour rate.

Time taken turning is a significant component of operating time in the field; typically in the order of 30%\(^{140}\) in sugarcane crops of similar overall biomass to that envisaged for banagrass. Overall field productivity can be anticipated to be in the order of 60%, equating to machine productivity in the order of 80 to 100 tons per hour.

Forage Harvester

While ample data relating to the performance of high capacity forage harvesters in crops such as alfalfa is available, data relating to performance in large grasses is more limited.

Sitkei\(^{141}\) notes that the process of cutting agricultural products can be related to the dry matter processing rate when all other factors (e.g., particle length) are constants. Analysis of his data indicates that for alfalfa, maize forage, and straw, the specific power consumption of the cutter head on a self-propelled forage harvester is in the order of 5.5 hp per ton of dry matter per hour for all three products. This specific power consumption is clearly also affected by the particle length selected.

An analysis of the typical productivity of large and small forage harvesters can be found in publications such as Prairie Agricultural Machinery Institute ("PAMI") reports\(^{142}\). This data, along with data from manufacturer websites\(^{143}\), allows relationships between machine productivity (tons of dry matter per hour pour rate) and power consumption for different crops being harvested to be assessed. This indicates that the specific power consumption of a wide range of machines for a range of crops can be assessed at approximately 9.5 hp per ton of dry matter per hour, at "typical" particle length settings. On this basis, a 500 hp forage harvester can be anticipated to have a dry matter pour rate of approximately 52 tons per hour. At a moisture content of 66%, this equates to a fresh weight pour rate of approximately 150 tons per hour. Since typical field efficiencies will be marginally higher than with the cane harvester, productivity can be anticipated to be 100 to 120 tons per hour. Considerations include the following.

- The forage harvester will have marginally higher productivity.
- A forage harvester is a “wheeled” machine, and therefore time taken to travel between fields is reduced.
- Overall maintenance costs for the forage harvester can be anticipated to be lower than for the sugarcane harvester.
- The load density of forage harvested material will be very significantly greater than the load density of the material produced by the sugarcane harvester. This will significantly impact on transport costs.


\(^{142}\) http://pami.ca/ (Accessed: 29 May 2012)

\(^{143}\) For example, www.krone.de. (Accessed: 30 Mar 2012)
3.6.3.5 Machine Stability and Functionality

While the sugarcane harvester envisioned for one-year cane in Hawaii is significantly more stable than traditional single-row harvesters on 6-foot wheel centers, the presence, associated weight, and cantilever effect of the harvester elevator can affect machine stability and, subsequently, productivity and functionality.

In contrast, the configuration of a forage harvester makes it inherently more stable. This is a consideration if banagrass is to be grown in areas less suitable for sugarcane, because of slope considerations.

3.6.3.6 Capital Cost versus Machine Capacity

Based on a nominal list price of approximately $375,000 for both the envisioned sugarcane harvester (375 hp) and a typical 500 hp forage harvester, the capital cost of the required fleet associated with the cane harvester option is marginally higher than the capital cost requirement for forage harvesters. More significantly, the lower product density of the material harvested by the sugarcane harvester will significantly impact on the capital equipment required for transport.

3.6.4 Harvesting System Selection

While initial trials in Hawaii involved harvesting banagrass with a sugarcane harvester, it is anticipated that a high productivity forage harvester would be a more cost effective and appropriate option.

In addition to a forage harvester, the following equipment will be required:

- Field-to-transloading pad haulout equipment to operate beside the harvester and to transport the harvested product to transloading sites
- Transport units to transfer the harvested product to the industrial facility

3.6.4.1 Harvesting Costs

Harvesting costs are composed of the costs associated with the harvester and in-field haulage, and field-to-mill transport. Table 3-31 provides a summary of the anticipated equipment levels and total capital costs involved in a harvesting operation for 5,000 acres and 10,000 acres of banagrass, on a single-shift (daylight) operation.
Table 3-31 indicates that three medium capacity forage harvesters would be required for 10,000 acres on a double-shift arrangement. The harvester group would require eight haulout units among them. The total capital cost will be in the order of $3.3 million. Fuel and maintenance costs are estimated at $2.30 per ton (fresh weight), and labor costs are estimated to be similar to a one-year cane harvesting operation, at $1.30 per ton. Ownership costs, depreciation and incidentals are not included.

<table>
<thead>
<tr>
<th>Area Harvested (acres)</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days/year for harvest</td>
<td>300</td>
</tr>
<tr>
<td>Nominal hrs/day operation</td>
<td>16</td>
</tr>
<tr>
<td><strong>Harvesters Required @ 75% Availability to Front</strong></td>
<td>4</td>
</tr>
<tr>
<td>Harvester cost inc accessories @ $475,000 $US</td>
<td>$1,900,000</td>
</tr>
<tr>
<td>Haulout sets required @ 90% availability to front.</td>
<td>8</td>
</tr>
<tr>
<td>Capital cost $145,000, tractors + haulouts</td>
<td>$1,160,000</td>
</tr>
<tr>
<td>Sundries including mobile workshop and spares, $200,000</td>
<td>$200,000</td>
</tr>
<tr>
<td><strong>Total Capital</strong></td>
<td><strong>$3,260,000</strong></td>
</tr>
<tr>
<td>Harvester fuel cost ($/t) at 4.00 $/gal</td>
<td>$2</td>
</tr>
<tr>
<td>Maintenance and consumables ( harvesters)</td>
<td>$0.49</td>
</tr>
<tr>
<td>Haulout fuel cost at 4.00 $/gal</td>
<td>$0.34</td>
</tr>
<tr>
<td>Haulout maintenance/t</td>
<td>$0.27</td>
</tr>
<tr>
<td><strong>Fuel and Maintenance ($/ton)</strong></td>
<td><strong>$2.30</strong></td>
</tr>
<tr>
<td><strong>Labor Costs ($/ton)</strong></td>
<td><strong>$1.30</strong></td>
</tr>
<tr>
<td><strong>Ownership Costs</strong></td>
<td><strong>$1.80</strong></td>
</tr>
<tr>
<td><strong>Harvesting Cost ($/ton)</strong></td>
<td><strong>$5.40</strong></td>
</tr>
<tr>
<td><strong>Service Life (years)</strong></td>
<td></td>
</tr>
<tr>
<td>Harvesters</td>
<td>5.1</td>
</tr>
<tr>
<td>Tractors</td>
<td>2.8</td>
</tr>
<tr>
<td>Trailers</td>
<td>4.6</td>
</tr>
</tbody>
</table>

* Ownership costs, depreciation and incidentals are assumed to be 50% of operating costs.
Field-to-mill transport costs can be based on current cost assumptions, as follows.

- The current haulage units have a “round trip” cost of approximately $215. However, since the fields that would probably be selected for banagrass will likely tend to be further afield, an average “round trip” cost of $250 is assumed.

- The capacity of the current haulage units is nominally 7,500 ft³. This capacity would be approximately retained if the units were fitted with tip-able hoppers.

- Assuming a load density of 20 lb/ft³, payload will be in the order of 150 tons. This is outside the limits of the payload capacity of the haul units. It is assumed that the maximum payload utilized will be 100 tons.

- Given a trip cost of $250, this equates to a transport cost of $2.50 per ton, fresh weight.

### 3.6.5 Agronomic Sustainability of Option #4: Type II Energycane and Energy Grasses (including Banagrass)

The production of annual harvest energy grasses, including banagrass, can be managed to achieve very high levels of environmental and agronomic sustainability. Key issues are as follows.

- While harvest will occur at least annually, the crop is harvested above ground level. This maintains a good degree of protection with respect to soil erosion from both water and wind.

- The configuration of the crop to match harvesting and transport equipment means that soil compaction can be managed advantageously, and the crop growth beds will not require regular tillage to mitigate the effect of random traffic.

- The crops are anticipated to have a “life” of up to 10 ratoons. Therefore, the program of heavy tillage for crop rejuvenation will be infrequent; typically with an anticipated repeat period of greater than five years.

These factors indicate that annual harvest energy grasses, including banagrass, can be farmed as part of an agronomically and environmentally sustainable farming system.
3.6.6 Option #4 Summary: Type II Energycane and Energy Grasses (including Banagrass)

Banagrass is a highly productive “tall grass”, which is increasingly being assessed as an energy crop for either direct combustion or for a range of conversion technologies. The anticipated fresh weight yield will be approximately 62.5 tons per acre per year, with a dry matter yield of approximately up to 20 tons of dry matter per acre per year. Annual harvest is assumed.

- The crop production methods utilized for banagrass and other energy grasses will be similar to the methods discussed for annual harvest sugarcane. Based on limited knowledge to-date, it is likely that the replant period may be increased as the crops typically ratoon aggressively.

- Land preparation and planting costs will initially be approximately one-third of current costs on the basis of cost/cropped cane per year. These costs will be reduced further with the adoption of minimum tillage replant strategies.

- Crop production costs (irrigation, fertilizer) will be similar on a per-acre basis to sugarcane.

- The environmental sustainability of the crop is anticipated to be very good. This is because there are very limited periods in which there is no ground cover, and it is anticipated that there will be significant periods between replant operations. Therefore, the harvest operation results in significant “stubble” and the soil is seldom bare and exposed to wind or rain.

- The preferred harvesting method is the use of forage harvesters. There are considerations related to operational matters associated with the terrain where the banagrass would be grown, load densities, and crop stool damage.

- The harvesting costs of banagrass are assumed to be marginally lower than the harvesting costs of sugarcane. The costs associated with harvesting 10,000 acres of banagrass are provided in Table 3-32.
Table 3-32: Summary of costs associated with the production of 10,000 acres of banagrass or energy grass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Per Acre</th>
<th>Total (10,000 acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Land Preparation and Planting Cost</td>
<td>Similar to sugarcane per acre</td>
<td></td>
</tr>
<tr>
<td>Annualized Land Preparation Cost</td>
<td>&lt;33% of sugarcane costs per acre</td>
<td></td>
</tr>
<tr>
<td>Irrigation, Fertigation and Management</td>
<td>Similar to Sugarcane</td>
<td></td>
</tr>
<tr>
<td>Crop Yield (dry matter/acre/year)</td>
<td>16.5 tons</td>
<td>165,000 tons</td>
</tr>
<tr>
<td>Biomass Fresh Weight Yield/acre/year</td>
<td>62.5 tons/acre</td>
<td>625,000 tons</td>
</tr>
<tr>
<td>Harvest and In-field Haulage Cost</td>
<td>$ 5.40</td>
<td>$ 3,375,000</td>
</tr>
<tr>
<td>Field-to-Mill Haulage</td>
<td>$ 2.50</td>
<td>$ 1,562,500</td>
</tr>
<tr>
<td>Total Harvesting Cost</td>
<td>$ 7.90</td>
<td>$ 4,937,500</td>
</tr>
</tbody>
</table>

Table 3-32 indicates that an area of 10,000 acres of banagrass or similar energy grass would produce approximately 625,000 tons (fresh weight) of biomass per year. The cost of harvesting and transport of the biomass would be approximately $7.90 per ton, or $4,937,500 per year. Cost per ton of dry matter and yields are provided in Activity 2’s Table 2-52. Banagrass produced the highest dry matter yield at the lowest cost per ton compared to the other grass crops on the Short List.
3.7 Crop Option #5: Tree Crops (including Giant Leucaena and Eucalyptus), Mechanically Harvested

3.7.1 Background: Tree Crops

In the discussion relating to tree crops in Activity 2 of the Biofuels Assessment, Osgood\textsuperscript{144} notes that tree crops, although lower yielding on an annual basis, have at least two distinct advantages over grass-type crops.

1) While the grasses need to be harvested on a defined schedule, trees can maintain biomass in the field and are not subject to a specific harvest date.

2) Tree biomass is typically at a lower moisture content than grass biomass.

This observation is essentially similar to those of Shepard et al.\textsuperscript{145} who note that woody biofuel feedstock has advantages relative to feedstock from other agricultural sources, because the perennial nature of the crop means that it can be “stored” in the field until needed. This eliminates double handling, storage costs, and related losses. A further advantage is the relative ease of storage of woody biofuel (relative to storage of grass-type product), particularly at higher moisture contents.

In a heavily modified environment, tree crops can have other advantages: Anon\textsuperscript{146}, in the Oil Mallee Development Plan developed in Western Australia, notes that strategic use of tree crops can be important to capture and use downslope migration of groundwater in shallow aquifers. This minimizes the potential for salinity in downslopes. The research (Giles, personal communication) also indicated that strategically placed bands of trees (typically with approximately 100 meters between bands) can more than compensate for the land area and water used, because of the windbreak effect that increases water-use efficiency in the main crop.

\textsuperscript{144} See Activity 2, Section 2.3.4.2 Potential Bioenergy Tree Crops.


The primary advantage of tree crops for the production of fiber at HC&S would be the following.

- Based on Australian experience in low rainfall areas, there is limited or no requirement for irrigation at planting, providing the time of planting coincides with the cooler, wet period of the year.

- Very high efficiency of incident rainfall inception and there is no requirement for irrigation for normal crop growth. The “saved” irrigation water is then potentially available to maximize crop production in other parts of the plantation.

- It is viable to plant tree crops in fields which are too rocky for the introduction of mechanized harvesting of sugarcane or energy grasses. However, surface rock would have to be managed to facilitate the continuous harvest strategies envisaged.

Multiple harvest tree crops can have significant advantages with respect to energy production. Wu et al.\textsuperscript{147} discuss the ratio of energy used in the production of tree crops for biomass relative to research into the production of Oil Mallee trees\textsuperscript{148} as a renewable energy source in that region. They note:

“(Eucalyptus) Mallee biomass production achieves strong energy gain with an energy ratio (the ratio of total energy outputs and total non-renewable energy inputs) of 41.7 and an energy productivity of 206.3 GJ/ha/year (78.6 MBTU/acre/year).”

They continue:

“This performance by a perennial woody crop is considerably better than that achievable by annual energy crops, i.e. canola (rapeseed) for biodiesel in the same region, where energy ratios are typically <7.0.”


\textsuperscript{148} “Oil Mallee trees” is the generic name for a group of approximately seven species of eucalypt well adapted to dryer environments in South-Western Australia.
They also note that:

“Almost 80% of total energy inputs during Mallee biomass production occur in biomass harvest and transport, arising mainly from the use of fossil fuels.”

It can be argued that similar energy ratios may be anticipated with the nominated tree species in Hawaii. The strategic utilization of tree crops can be argued to meet any future energy sustainability targets.

The efficient production of tree crops (for mechanical harvesting for woodchip for fiber) relies on the presentation of the trees for efficient harvesting. The most efficient harvesting systems utilize continuously moving “over-the-row” machines. This involves the following.

- Trees are grown in a hedgerow arrangement at a spacing which is compatible with the harvesting operation.

- The chipped trees are collected in field transport units similar to the units used for transporting sugarcane from the chopper harvester to the field-to-mill transport units.

### 3.7.2 Selected Tree Species for Maui

In Activity 2, analysis of available data resulted in the identification of two genera of trees for a Short List of crops for further consideration for bioenergy use in Hawaii:

- Giant leucaena (*Leucaena leucocephala*), as an alternative because of its suitability for low-land sites

- Several species of *Eucalyptus* spp., as an alternative for up-land sites

Key attributes noted for the selected genera are detailed in Activity 2 summarized in Sections 3.7.2.1 Giant Leucaena and Section 3.7.2.2 Eucalyptus.
3.7.2.1 Giant Leucaena (*Leucaena leucocephala*, K636) and other Leucaena selections and hybrids

Activity 2\textsuperscript{149} notes typical characteristics as:

- Typically yield 8 to 10 tons per acre per year, dry weight
- Annual harvest is envisaged
- Reestablishment after harvest is by coppice growth and are expected, with good management, to produce for 20 or more years after establishment
- Tree structure tends to be multi-stem branching which impacts on harvesting strategy\textsuperscript{150}

Shelton and Brewbaker\textsuperscript{151} note that Leucaena is “a thornless long-lived shrub or tree which may grow to heights of 7-18 m”. They also note that:

> “Leucaena is capable of producing a large volume of a medium-light hardwood for fuel (specific gravity of 0.5-0.75) with low moisture and a high heating value, and makes excellent charcoal, producing little ash and smoke”.

As a fodder crop, Shelton and Brewbaker note productivity of 1.3 to 13 tons of dry matter per acre per year (3 to 30 tonnes of dry matter per hectare per year) with harvests every 6 to 8 weeks in high yielding environments and appropriate varieties. This equates to a fresh weight biomass yield of approximately 3.25 to 32.5 tons (fresh weight) per year, assuming 60% moisture content. They also note that in trials in Australia, the wood fraction of trees harvested at 9 months was typically around 60% of the fresh weight, and that under grazing conditions, the half-life\textsuperscript{152} of leucaena is thought to be approximately 50 years.

\textsuperscript{149} See Activity 2, Section 2.3.4.2 Potential Bioenergy Tree Crops, 12) Giant Leucaena.
\textsuperscript{150} This is especially true for coppice stands.
\textsuperscript{151} http://www.fao.org/ag/AGP/AGPC/doc/Publicat/Gutt-shel/x5556e06.htm
Accessed: Mar 2012
\textsuperscript{152} In this context, half-life indicates the time before approximately 50% of the initial trees planted have died.
3.7.2.2 **Eucalyptus** (*Eucalyptus* spp. and hybrids)

Activity 2\(^{153}\) notes typical characteristics of eucalyptus as:

- Well known for producing high yields of high quality woody biomass
- Can be grown on very short rotations of one year, or longer rotations up to seven years in subtropical or tropical environments
- Yields of 10 to 14 tons of dry biomass per acre per year were obtained in Hawaii experimental sites (Osgood and Dudley, 1993)
- Typically, eucalyptus cultivars are selected for single-stem upright stature, and propagated either by seed from selected, high yielding breeding lines or clonally from selected individuals\(^{154}\)

Further useful information is available from research into farmed eucalyptus in Southern Australia, with the performance of systems in dryer areas of significance. Both Maui and Southern Australia have winter dominant rainfall. Australian data indicates that appropriate selection of variety can allow useful productivity to be achieved in very low rainfall areas without additional water application.

Hobbs\(^{155}\) records that in the 14- to 22-inch rainfall belt in Western Australia, yields for various species of Eucalyptus Mallee of 2.2 to 6.8 tons of dry matter per acre per year (5 to 15 tonnes of dry matter per hectare per year) were typically observed in two-row belt configurations at an age range of 7 to 11 years. This would approximately equate to a fresh weight biomass production of 4.9 to 15 tons per acre per year, assuming 55% moisture content of the tree at harvest. Hobbs also notes that the band planting configuration nominally yields around 50% higher than full-field plantings.

Bartle et al.\(^{156}\) reported similar water-use efficiency gains in Eucalyptus Mallee trees planted in bands, after accounting for “edge effects”. The advantage of band planting was

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\(^{153}\) See Activity 2, Section 2.3.4.2 Potential Bioenergy Tree Crops, 13) Eucalyptus.

\(^{154}\) Trees in coppice stands have multiple stems which will impact harvest.


noted as potentially related to the ability of the tree bands to intercept additional water at depths not utilized by the surrounding crop.

Eucalyptus Mallee is adapted for low rainfall areas and has a multi-stem sprawling characteristic, rather than single upright stem. The observed yields tend to be competitive with those indicated to-date in Hawaii. This indicates that high productivity is probably possible in the drier areas of Maui without supplementary irrigation, providing varietal selection and spatial arrangement of the trees are appropriate.

Research in Australia with large scale plantings of leucaena as cattle fodder and Eucalyptus Mallee as a short rotation woody biomass source therefore provide useful additional information for consideration in the selection of tree crops in the dryer areas of Maui, and in areas less suited to sugarcane production.

3.7.3 Planting and Establishment.

Key planting and establishment issues for both tree crops on the Short List are:

- Site Selection and terrain constraints
- Tree spacing configuration, including land preparation and establishment costs
- Irrigation and crop management

3.7.3.1 Site Selection and Allowable Terrain

It is envisaged that steeper land, less productive land, or areas that are generally less suitable for sugarcane production (e.g., rocky land) would be considered for the appropriate tree-crop. Generally, leucaena is better adapted to lower elevations and eucalyptus is better adapted for higher elevations.

The allowable terrain is primarily driven by the constraints of harvesting systems. Virtually all land that has been developed for sugarcane is envisaged as being suitable for tree-crops. Some additional areas not currently utilized for sugarcane may also be potentially suitable. A key issue will be the feasibility of harvesting small localized areas with specialist harvesting equipment.

3.7.3.2 Tree Spacing Configuration

Tree spacing configuration affects many factors; from initial site establishment costs to the impact on final harvesting technique and costs. Optimizing tree spacing configuration with respect to harvest period is important in terms of both biomass yield and biomass characteristics.
General considerations indicate that higher planting densities are related to higher early total biomass productivity. However, the leaf-and-twig to wood-biomass ratio is changed by both spacing/density and age at harvest. The findings reported in the “Oil Mallee Development Plan” are similar to the observations of Giles and Harris. They note that in harvested product (whole tree harvested eucalyptus), the proportion of woodchip, leaf and assorted bark, and small twigs is approximately one-third each, but this varies widely according to tree species and age at harvest. As the aim of utilization of the harvest product is ultimately as a fuel, the proportion of leaf, bark, and twigs may need to be minimized because these components:

- are typically higher in ash
- will be of higher moisture content at time of harvest
- reduce load bulk density relative to clean woodchip

These effects can be considered to relate to both leucaena and eucalyptus

**Leucaena**

When planted as either a fodder crop or as a biomass crop, leucaena is typically planted in rows. When cultivated as a fodder crop, various row configurations have been reported. In this application, the primary goal is the high production of leaf material, with wood production minimized. Co-production of grassy fodder is also encouraged.

- The general recommendation in Australia (Buck) is for a row spacing of 16 to 40 feet (5 to 12 meters), depending on the fertility and potential productivity of the site. Wider spacing is designed to allow higher grass production in the row interspaces. For tree biomass production, closer row spacing would be more appropriate.

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• Shenond and Brewbaker\textsuperscript{160} note that planted rows are typically at 10 to 33 foot (3 to 10 meter) spacing in high productivity planting as a pasture tree.

The planting of leucaena for wood chips requires alternative strategies for optimization of productivity of the highest value components of the plant. Brewbaker et al.\textsuperscript{161} note that:

“Diameter and height development of Leucaena is influenced by per hectare populations. Generally, diameter growth is affected more by high populations than height growth. Thus, spacing is an effective management tool which when considered in conjunction with rotation age can be used by the manager to produce material of suitable diameter and length for many different purposes.”

Van Den Beldt and Brewbaker\textsuperscript{162} also note that plant spacing configuration can be used as a management tool, with the three considerations, the:

• use intended for the product
• site quality
• age at which a particular spacing will inhibit growth

They note that higher populations lessen the time of crown closure, result in smaller diameter trunks, and reduce the time required to complete one rotation. From this, they derive that:

“maximum total wood yield of Leucaena, without regard to wood quality is achieved by high population densities of between 10,000 and 20,000 trees/ha (4,050 and 8,100 trees/acre).”

\textsuperscript{160} http://www.fao.org/ag/AGP/AGPC/doc/Publicat/Gutt-shel/x5556e06.htm (Accessed: Mar 2012)


This equates to approximately a 3 foot 4 inch square spacing for 4,050 trees per acre and 2 foot 3 inch square spacing for 8,100 plants per acre. These spacing configurations are generally not compatible with mechanized harvesting processes. Moving away from a square pattern to a row configuration of 6 to 8 feet and a tree population of 4,050 trees per acre results in spacing between plants along the row of only 16 to 21 inches.

These populations are either four or eight times higher than the populations used in trials in Hoolehua, Molokai, and Puunene, Maui (as reported in Activity 2), where the typical established plant population was 1,012 plants per acre. Assuming planting in a “square configuration”, this equates to row and intra-row spacing of 6.5 feet. Alternatively, at a row spacing of 6 feet, this equates to an intra-row spacing of 86 inches.

Yields are typically driven by water availability, and Brewbaker et al.\textsuperscript{163} note that maximum rain-fed yields with leucaena are typically achieved in environments receiving approximately 60 inches per year, without an excessively long dry period. They quote wood yields under “good conditions” in the range of 5.8 to 14.3 tons (fresh weight) per acre per year. Given the typical relationship of approximately 65% of the biomass fresh weight being leaf and twig, this equates to total biomass yields of 9 to 22 tons per acre per year.

The yields in trials on Maui and Molokai achieved approximately 10 tons of dry matter per acre per year biomass production at five years after planting.\textsuperscript{164} Stem diameter at time of harvest was reported as 3.9 inches. This yield is then consistent with expectations for the lower plant populations in a less optimal environment than the trials reported by Brewbaker et al.

For the purposes of further analysis, assumed parameters will be:

- 10 tons of dry matter per acre per year biomass production under good conditions
- 6 tons of dry matter per acre per year under more marginal conditions
- 8 tons of dry matter per acre per year, average yield
- population of 1,000 to 2,000 trees per acre

\textsuperscript{163} Brewbaker - \url{http://www.fao.org/ag/AGP/AGPC/doc/Publicat/Gutt-shel/x5556e06.htm} (Accessed: Mar 2013)

\textsuperscript{164} These Hawaii sites were irrigated. It is commonly assumed that commercial production sites will be irrigated.
• single-row configuration to match harvesting equipment, i.e., 6 feet or 8 feet spacing between tree rows

• harvest period of 3 to 4 years

Different cultivars of leucaena can be expected to develop with different tree architectures (Buck\textsuperscript{165}). However, as the tree develops, it is probable that the stem number will be reduced. Conversely, the process of coppicing can be anticipated to increase the number of stems per tree. While the initial alternative covered was that leucaena would be suitable for annual harvest, increasing the time between harvests can be anticipated to increase the wood proportion of the product harvested.

Figure 3-42 shows a leucaena stand planted primarily as renewable fuel-wood on Negros Island in the Philippines at a demonstrably much greater spacing. A range of tree architectures, ranging from single-stem to multi-stem configurations, are visible. Few, if any, silvicultural operations have been undertaken on these trees. The age of the trees is not known.

Eucalyptus

Trials in Maui (of Eucalyptus grandis) and Molokai (of E. Camaldulensis) reported in Activity 2 indicate biomass yields of 4.4 to 7.5 tons of dry matter per acre per year biomass, at the harvest age of 5 years and 1,012 trees per acre. This equates to tree weights of 124 to 165 pounds of dry matter per tree. (This assumes above-ground biomass only.) At an assumed moisture content of 50 to 60% (55% assumed), this equates to a fresh weight of 9.7 to 16.7 tons (fresh weight) per acre per year.

In forestry applications, the spacing of clonal eucalyptus is optimized to maximize yield of millable timber. In this application, the fields are over-planted and strategically thinned. Geoff\textsuperscript{166} notes:

“This is largely because the aim of thinning is almost always to ensure that stem diameters attain a desired threshold as early as possible in the life of a stand”.

In another study into eucalyptus growth rates, Barnardo et al.\textsuperscript{167} noted that:

“The growth, biomass, and nutrient distribution of Eucalyptus camaldulensis, E. pellita and E. urophylla were evaluated at ages 15, 31 and 41 months at spacing levels of 3 x 1.5, 3 x 3 and 3 x 4 meters (10ft x 5ft, 10ft x 10ft and 10ft x 13ft) for growth and aboveground and root components for growth and dry biomass in the Cerrado region of Minas Gerais, Brazil. The average whole-tree weight (aboveground + roots) at age 41 months (3x1.5 m, 3x3 m and 4x3 m spacing levels averaged together) was 54.3, 42.4 and 41.2 kg/tree (119, 93.3 and 91 lb/tree) for E. urophylla, E. camaldulensis and E. pellita. In all cases, the highest total biomass per tree occurs at the 4x3 (13ft


\textsuperscript{167} Bernardo, A., G. Reis, M. Reis and R. Harrison. Effect of spacing on Eucalyptus camaldulensis, E. pellita and E. urophylla plantations in southeastern Brazil: Growth & biomass
x 10ft) m spacing level, but the highest growth per hectare occurs at the 3x1.5 m (10ft x 5ft) spacing. Differences in percent distribution of biomass among tree parts were noted according to spacing and species.”

The plant populations equate to 104 to 276 trees per acre. For *Eucalyptus camaldulensis*, the average tree weight was 93.3 pounds per tree. This analysis is consistent with the analyses which indicate higher initial population maximizes early biomass accumulation, which is typically a goal of tree production for biomass. Additional considerations will relate to the anticipated composition of the tree components in the harvested product, and the associated impact on downstream use.

In Australia, Schmidt et al.\textsuperscript{168} noted:

> “The mallee coppice crops are typically grown in belt configurations, most commonly in four rows per belt, but increasingly with two rows, with the inter-belt alleys varying, from 40 to 100 metres or more across. Row spacing within the belt is normally 2 metres and stem spacing within the row is nominally 1.5 metres (Giles and Harris 2003)\textsuperscript{169}. Early indications from spacing trials are that the intra-row spacing could be increased without reducing crop production per metre of row, which would significantly reduce establishment costs and increase the size of each mallee at harvest age. Such belts were originally established with stockings as high as 2,600 stems per hectare (1052 stems/acre), but rates of establishment as low as 1,600 sp/ha (650/acre) may maintain the same productivity per unit area planted, while reducing the costs of establishment and harvesting.”

For the purposes of further analysis, it is assumed that eucalyptus will achieve:

- 10 tons of dry matter per acre per year biomass production under good conditions


• 6 tons of dry matter per acre per year under more marginal conditions

• 8 tons of dry matter per acre per year, on average

The following is also assumed:

• Population of 1,000 trees per acre

• Single-row configuration to match harvesting equipment, i.e., 6 foot or 8 foot spacing between tree rows

• Harvest period 4 to 5 years

### 3.7.3.3 Planting Methods and Cost

The planting method, as well as configuration, impacts on planting costs, as do a number of other production related parameters.

As noted in Activity 2, it is likely that both tree species (leucaena and eucalyptus) will require irrigation at least for establishment on dry Maui sites. This would clearly increase productivity. However, considerations include the following.

• Some areas under consideration for tree-crops would have adequate rainfall for high productivity tree crops. However, the decision to plant trees will likely be based on the unsuitability of the land for machine harvested one-year sugarcane, including consideration of issues such as rockiness and slope, rather than rainfall.

• Maui has a winter-dominant rainfall pattern. Based on experience in Southern Australia which has similar rainfall patterns, tree seedlings can be very effectively established without irrigation even in sandy soils with rainfall of less than 12 inches per year.

• It is likely that, in the configuration of trees that is adopted, an irrigation technology similar to the one used for sugarcane will be applicable. The drip lines could be withdrawn and re-used after tree establishment.

The decision as to whether to use irrigation for crop establishment would therefore be made on a site-by-site basis.
**Giant Leucaena**

Leucaena can either be direct planted or the seeds can be grown in a nursery and the seedlings transplanted. When grown as a fodder crop, leucaena is typically direct planted\(^{170}\). Van Den Beldt and Brewbaker\(^{171}\) note that direct planting is increasingly becoming the method of choice for planting leucaena for biomass production.

Sheldon and Brewbaker\(^{172}\) recommend that seeding rates of 2 to 3 pounds per acre are appropriate for forage planting applications. However, the seeding rate will be different for biomass production where row spacing is significantly reduced, and intra-row spacing will be greater. In the absence of significant data related to either seed-weight or anticipated establishment rates in a direct seeding application, planting rates in the order of 3 to 4 pounds per acre can be assumed. For pasture applications, the seeding operation is typically undertaken with appropriately modified grain row-crop planters. A similar strategy would be used for biomass stands.

Sheldon and Brewbaker also note that the seed should be mechanically scarified and inoculated with correct rhizobium. The seed should be planted into wet soil, sufficiently deep to stay wet for a week, but no deeper than 2 inches. They also suggest running press wheels to the side of the seed, not over the top. It is anticipated that strategies such as modifying the metering mechanism in the planter to closely “group” several seeds at the nominal target intra-row spacing would result in more optimal final plant configurations for biomass harvesting. Many researchers note that the crop has a high phosphorus requirement and this should be applied at planting.

Buck\(^{173}\) notes that leucaena is very susceptible to soil compaction. He noted trials in Central Queensland in Australia where a 75% increase in leucaena productivity was achieved in plots with pre-establishment ripping to a depth of 28 to 30 inches versus plots

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\(^{172}\) Sheldon and Brewbaker

where only shallow land preparation strategies were used in pasture fields. While leucaena can be planted in poor soils, it requires good soils for maximum productivity (Anon\textsuperscript{174}).

The land preparation and post-planting components of crop establishment costs associated with leucaena can be equated to similar costs for sugarcane, with the key activities being:

- Land preparation, including ripping and discing
- Planting the seed with maize/sorghum planter
- Placement of temporary drip irrigation tube, if irrigation is to be applied
- Post planting herbicide application

The total cost of the actual planting operation for leucaena will, however, be substantially lower than the costs associated with the planting operation for sugarcane. This is because the seed cost will be minimal compared with the cost of the cane seed supply and planting operations.

**Eucalyptus**

Eucalyptus hybrids are typically clonally propagated, with the small plants planted into a furrow, utilizing appropriate seedling planting equipment. The primary costs will be:

- land preparation
- supply of plantlets and planting
- silvicultural operations after planting

As with leucaena, maximum establishment and productivity will be achieved by the appropriate depth of tillage prior to planting, as well as good tilth in the zone where the plants will be placed.

The supply of the cloned plantlets will typically be a cost of greater significance than seed costs for leucaena. The plantlets would typically be raised in a facility off-site and transported to site for planting.

Hobbs et al.\textsuperscript{175}, referring to the Oil Mallee work in low rainfall zones in Australia, notes that:

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“Planting densities were set at 1,000 plants per hectare (400 plants/ac) for all biomass industry species groups except for fodder shrubs which uses 1,500 shrubs per hectare (600 plants/acre). Establishment costs are based on those reported by Hobbs et al. (2007a) for broadacre biomass industries. For this study we have used an establishment cost of $875/ha ($354/ac) for trees and mallees and $825/ha ($335/ac) for fodder shrubs.”

Approximate parity can be assumed between Australian and Hawaiian costs and currency.

Hobbs\textsuperscript{176} also notes that:

“However, broadacre agroforestry establishment costs in flat, simple and sandy landscapes are likely to be around 15% less than this figure. Average annual maintenance costs have been set at $10/ha/year ($4/ac/year) to include occasional and sporadic activities such as firebreak control, supplementary fertilisers, follow-up weed and pest control.”

Giles (personal communication) indicates that the seedling cost is assumed to be approximately $0.20 each. Clonally propagated seedlings will be assumed to cost $0.30 each.

<table>
<thead>
<tr>
<th>Plant Density and Type (plants /acre)</th>
<th>Site Planning, Setup and Land Preparation ($/acre)</th>
<th>Seedlings, Planting and Initial Watering ($/acre)</th>
<th>Weed Management and Control ($/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Production Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trees @ 400/acre</td>
<td>$125</td>
<td>$140</td>
<td>$35</td>
</tr>
<tr>
<td>Shrubs @ 600/acre</td>
<td>$120</td>
<td>$200</td>
<td>$20</td>
</tr>
</tbody>
</table>

In addition to these costs, there should be an allowance for:

- Ripping the field, estimated at $150 per acre
- The increased cost of clonally propagated trees over seedlings
- The anticipated increased seedling population (1000 per acre)

An allowance for initial irrigation or fertilization is not necessary.

Summary

The estimated costs for land preparation, planting and initial management, without allowance for any irrigation or fertilizer application, is presented in the Table 3-33 below. U.S.-dollars are assumed.

| Table 3-33: Estimated costs for land preparation, planting and initial management of tree crops |
|-----------------------------------------------------|-----------------|-----------------|
| Plant density (plants/acre)                         | Leucaena        | Eucalyptus      |
| Plant/seed cost                                     | $50/acre        | $300/acre       |
| Ripping and land preparation                        | $275/acre       | $275/acre       |
| Planting                                            | $30/acre        | $60/acre        |
| Weed management                                     | $40/acre        | $40/acre        |
| Establishment cost                                  | $395/acre       | $675/acre       |

Note: • Allowance for any irrigation and fertilizer application not included  
• Direct seeding has not been successful in Hawaii for leucaena. Establishment will require irrigation.

For analysis purposes, the cost of land preparation and planting, but not including irrigation or fertilizer, is $395 per acre for leucaena and $675 per acre for eucalyptus. Assuming approximately equivalent areas of each species, the average cost would be $535 per acre.
3.7.4 Harvesting

3.7.4.1 Time of Harvest.

While a benefit of trees as a biomass crop is that they can be harvested at a time that suits the downstream users, some consideration must be given to the coppicing ability of the tree. Shepard\textsuperscript{177} notes that coppicing ability is critical for trees grown for biomass. However, Giles (personal communication) indicates that the phase in the annual growth cycle at harvest can be a significant factor in coppicing performance, with better results often achieved from harvest during cooler wetter months. Conversely, traffic-ability and access could potentially be issues that constrain harvesting activity during the wet times of the year.

3.7.4.2 Harvesting Systems

Harvesting systems that can be used for tree crops are extremely varied. Hartsough\textsuperscript{178} notes that a harvesting system for short rotation woody crops (“SRWC”) may include five functions:

- Felling
- In-stand transport (primary transport: skidding or forwarding)
- Separation of pulpable wood from residues (only for pulp production)
- Chipping or other comminution
- Stand to facility (secondary) transport.

He notes that two or more of these functions may be combined into one operation, making the system more compact and utilizing less equipment. He also notes that while separation of wood and residues is essential for end-uses such as pulp, for biomass usage, all components of the tree can typically be utilized.


Hartsough categorizes SRWC as “small” if the diameter at breast height (“DBH”) is less than 3 inches (75 millimeters) and large if above that. He notes that for small material, two strategies:

1) cut and chip
2) cut-only

are the most successful. He notes that “cut and forward” concepts are not successful for this type of material. He also notes that cut and chip machines offer the lowest harvesting costs, and that machines based on agricultural harvesters have generally been most successful.

Considerable research has been undertaken into the harvesting of “small” material, driven by the rapid growth of SRWC in Europe and in particular the commercial harvest of tree species such as willow. Stuart\textsuperscript{179} notes:

“Rotations which result in stems being harvested when they are between 2 and 3 cm (app 1”) at severance height and less than 4 to 5 m (13-16 ft) tall can usually be harvested by heavy-duty agricultural (corn and sugar cane) equipment. Material over 15 cm (6”) on the stump can usually be harvested with conventional forestry equipment--feller-bunchers, skidders, and processors.”

### 3.7.4.3 Equipment for Thinner Trees

While Stuart classifies small trees suitable for harvesting with large agricultural harvesting equipment as trees less than 1-inch in diameter, Hartsough\textsuperscript{180} quotes the use of this type of equipment as being suitable for trees (typically) with a base diameter of less than 3 inches.

Agricultural machine-based equipment can be based on sugarcane harvesters and large self-propelled forage harvesters. Initial work in Europe with an Austoft harvester based on the Austoft 7000 sugarcane harvester has been reported by numerous researchers. Hartsough notes that Claas, and more recently other manufacturers, has developed gathering heads for forage harvesters for harvesting short rotation trees. The very competitive capital


cost for available installed power has generally meant that these systems have become the accepted machine, with Hartsough quoting productivities up to 50 tons (oven dried) per hour while cutting for large machines.

The original advantage perceived for the sugarcane harvester based concept was the rugged design, particularly in the area of basecutting. The original Austoft SRWC harvester incorporated a modification to the normal basecutter box, whereby high speed saws were mounted concentrically and underneath the basecutter discs. The basecutter discs and legs then rotated at a speed matching the internal feedroller tip speed, giving positive feed of material into the machine.

This concept has now been further developed for forage harvesters. Figure 3-43 illustrates one example; the “FP130” gathering head offered for forage harvesters by the Case-NH group. This machine utilizes a heavy duty severing and gathering system based on Case sugarcane harvester basecutter components. The advertised capacity is for trunk diameters up to approximately 3”.

Figure 3-43: Heavy duty gathering front developed from sugarcane harvester components on a forage harvester
The leucaena harvester developed in Australia by Bundaberg Mobile Machinery is based on a Case sugarcane harvester, with the sugarcane billeting and trash extraction systems replaced by a heavy duty drum chipper. The basecutter arrangement also incorporates the developments initially made by Austoft for European SRWC harvesters, with high speed saws concentrically mounted below the basecutter legs. The machine also retains gathering spirals to assist with aligning the crop. The machine is designed for harvesting the crop as a forage product, not as a biomass product for fuel.

All of these machines rely on the concept initially developed with sugarcane harvesters, where the crop is “preloaded” by pushing (prior to the basecutting operation) to promote butt-first feed into the feedtrain. This concept clearly has limitations with respect to the diameter and stiffness of the trees that can be harvested with this type of equipment. These machines are potentially suitable for short rotation harvesting of leucaena; for instance, with a one- to two-year harvest interval. They would generally be considered unsuitable for harvesting older leucaena or eucalyptus. Apart from the issue of the machine being able to feed trunks of the trees of the size anticipated, there are other potentially very significant issues, such as:

- the force required by the machine for “knockdown”
- the potential damage to the root system of the tree from the degree of preloading
- the probability of splits transferring down into the stump

### 3.7.4.4 Equipment for “Intermediate” Trees

Stuart notes that stems in the 1-inch to 6-inch DBH range do not fit easily with either area or single-stem acquisition technology. He notes that area-based acquisition and severance equipment, such as combine headers, work best with a uniform distribution of material and a relatively homogeneous plant size. Single-stem technologies, which can be generalized to single-stool technologies, require a plant spacing open enough to get the implement on the stem. Stuart then notes that stems between these bounds (1-inch and 6-inches) have historically been the domain of land-clearing and right-of-way maintenance contractors. The equipment available (bush hogs, stirrup flails, chain flails) has been designed to destroy or reduce the material and leave it on-site as mulch, with no consideration of capturing it as a marketable product. Survivability of stools and minimization of coppicing damage have not been design considerations. In fact, having few stems survive the bush hog, flail, or other treatment has been considered the mark of a “good job”.
Some development in equipment for continuous harvesting product in this size range has been undertaken by various groups. McLauchlan et al. developed a flail type harvester for conditions that were considered too heavy for agricultural harvester based equipment. The harvesting system they developed was apparently commercialized as the “Felcon Bio-Harvester”, and is illustrated in Figure 3-44.

In comments on the performance of this equipment, McLauchlan noted that most success was with trees of less than 60 millimeter diameter. Below this diameter, the unit was successful in collecting most of the product. As tree diameter increased, losses increased. Similar comments were made by Hartsough, who noted that the problem with this machine concept is the ability to capture and comminute the material, and that machines that undertake the capturing and severing of the material in operations separate to the comminution are likely to be more efficient.

Figure 3-44: Machine designed for "intermediate" biomass, utilizing a flail head

### 3.7.4.5 Equipment for Larger Trees

Strategies for larger trees (greater than 3 inches DBH) are usually based around the use of forestry based machines. Typically, the logs are cut and then either forwarded to a site for further processing, or to a chipper. These systems have an emphasis on the

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production of either log wood or chips; with strategies such as de-limbing and debarking prior to chipping aiming to give a different product quality to that achieved by chipping the entire tree. When the final product is woodchip, a range of machines are now available that can move along a line of felled trees and process them. One such machine is shown in Figure 3-45 below. The machine utilizes an integrated lifting arm to feed the tree trunks into the feeding chute of the chipper unit.

Figure 3-45: Mobile chipper unit used to move along windrows and feed the trees with an integrated lifting arm

Analysis undertaken on the requirements for harvesting short rotation woody crops (Giles, personal communication) indicates that this strategy will typically result in harvesting costs in excess of $45 per ton. The need for a low cost harvesting solution for the development of the Oil Mallee industry spurred significant R&D on low cost harvesting strategies in Australia. The form of the mallee stems is crooked, often forked and multiple stems grow from the parent plant rootstock. Because of these characteristics, concepts such as felling, followed by traditional log handling, were not appropriate, and the concept of an “over-the-row” harvester was deemed necessary.

In a Giles and Harris\textsuperscript{182} review of literature, it was reported that Hartsough and Spinelli (2000) conducted a survey of continuous softwood harvesting operations and found that for a given total machine power, the average hourly productivity of continuous

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The layout (of the commercial prototype developed) incorporated an implement attachment (harvester head) for a utility tractor (Claas Xerion Saddle Trac). The machine demonstrated harvesting operations was up to an order of magnitude higher than for stationary systems (where the material was brought for processing). They then argued that a key requirement to minimize the cost of harvesting is a continuous in-field operation.

The research program that followed led to the development of a heavy duty biomass harvester capable of continuously harvesting trees with stump diameters up to 8 inches with branching characteristics. The machine is illustrated in Figure 3-46 and Figure 3-47. Harris and Giles note that key features incorporated into the concept include the following.

- The stem cutting action is directly coupled with the chipper process by mounting the chipper on the harvester.

- The trees are crushed just behind the severing saw for two purposes.
  1. To maximize control over the severed tree.
  2. The crushing reduces the lower crowns of trees or any structure to a relatively consistent two dimensional shape. This allows the handling of very diverse tree structures.

The tree is held upright throughout this operation.

- These features eliminate additional stem handling and maintain an even flow of material to the chipper to maximize chipper performance.

Figure 3-46 and Figure 3-47: Biosystems Engineering Prototype Woody Crop Harvester
the capability of high productivity in a range of conditions, and is currently undergoing commercialization.

Analysis of harvesting costs for this type of equipment by Sandell\textsuperscript{183} has indicated that based on production costs and the productivities being achieved under trial conditions, harvesting costs (including, in-field haulage, but not including field-to-mill haulage) of $15 to $20/t are probable. Transport costs from the field-edge to the mill can be anticipated to be similar to a product such as forage harvested banana grass, since both products have similar bulk densities.

Analysis of anticipated harvesting costs is based on the following.

- Average annual yield of 8 t\textsubscript{dm}/acre, with a four year harvest period for both tree species being reviewed.
- The harvester is a heavy duty “over-the-row” continuous chipper-harvester.
- Haulout units of capacity 875 ft\textsuperscript{3} will be used to transfer the material from the harvesters to the field-mill transport units. Tractors will be 130 hp.
- Continued use of the current field-mill haulage units, fitted with a modified basket. The payload will be 100 t, and haulage cost will be $2.50/t.

The specifications of the harvester are:

- Purchase cost .......... $650,000
- Power .......................... 500 hp
- Specific power usage ........ 15 hp/lb\textsubscript{dm}/sec
- Functional life ............ 10,000 hrs

Table 3-34 summarizes the key parameters related to harvesting cost.

<table>
<thead>
<tr>
<th>Table 3-34: Summary of key harvesting cost parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area of crop (acres)</strong></td>
</tr>
<tr>
<td><strong>Annual area harvested at 4-year harvest period</strong></td>
</tr>
<tr>
<td><strong>Fresh weight tonnage harvested/year at 18 t/ac/year</strong></td>
</tr>
<tr>
<td><strong>Dry matter tonnage/year at 55% moisture content</strong></td>
</tr>
<tr>
<td><strong>Days/year for harvest</strong></td>
</tr>
<tr>
<td><strong>nominal hrs/day operation</strong></td>
</tr>
<tr>
<td><strong>Harvesters required at 75% availability to work</strong></td>
</tr>
<tr>
<td>Harvester cost incl. accessories at $650,000 ($-US)</td>
</tr>
<tr>
<td>Haulout sets required at 85% availability to work</td>
</tr>
<tr>
<td>Capital cost, tractors at $60,000 each</td>
</tr>
<tr>
<td>Sundries including mobile workshop and spares</td>
</tr>
<tr>
<td><strong>Total Capital</strong></td>
</tr>
<tr>
<td>Harvester fuel cost ($/ton) at 4.00 $/gal</td>
</tr>
<tr>
<td>Maintenance and consumables ($/ton, harvesters)</td>
</tr>
<tr>
<td>Haulout fuel cost ($/ton) at 4.00 $/gal</td>
</tr>
<tr>
<td>Haulout maintenance ($/ton)</td>
</tr>
<tr>
<td><strong>Fuel and Maintenance ($/ton)</strong></td>
</tr>
<tr>
<td>Labor Costs ($/ton, harvest and haulout)</td>
</tr>
<tr>
<td>Ownership Costs ($/ton, harvesters)</td>
</tr>
<tr>
<td>Ownership Costs ($/ton, haulout units)</td>
</tr>
<tr>
<td><strong>Harvesting Cost ($/ton)</strong></td>
</tr>
<tr>
<td>Field to Mill Haulage at 2.50 $/ton</td>
</tr>
<tr>
<td><strong>Total Harvesting Costs ($/ton)</strong></td>
</tr>
</tbody>
</table>

Table 3-34 indicates a harvesting and haulage cost of approximately $22 per ton of fresh weight product delivered.

### 3.7.4.6 Product Specification and Pre-Processing

The chipped biomass in its unsorted state is a mixture of wood chip, leaf, and residues of assorted fine chip material, bark and small twigs. The proportion of wood, leaf and residues is about one-third each, but these values vary widely according to tree species and age at harvest. Younger, smaller trees have high proportions of leaf and less wood. The
proportion of wood increases with age (Giles and Harris, 2003). Wood fractions in excess of 40% are likely to be achieved given the tree size envisaged at harvest.

Chipping of whole trees introduces a number of considerations, including the following.

- Chipping produces long particles, such as sections of small branches, which add significantly to the difficulty of handling the bulk biomass (McCormack et al., 2009).

- Clean eucalyptus wood chip is relatively stable and is commonly stored in open stacks for periods of several weeks without significant loss of quality (e.g., wood chip export and paper mills). The mixed material in chipped form is liable to decompose significantly. It is preferable to sort the leaf and residues from the wood chip if wood chip is to be stored for any period (Giles and Harris, 2003).

A chip cleaning stage to separate foliage/leaf and clean chip may be an appropriate strategy. This would allow stable storage of the chip, while the foliage and fine material could be dried or used as quickly as possible.

### 3.7.5 Agronomic Sustainability

Simpson et al.\(^\text{184}\) note that there is significant debate as to the environmental impact, and in particular the impact with respect to soil erosion, from short rotation woody crops. They note that any effect will be at its greatest during the first two to three months associated with land preparation and crop establishment. They argue that the use of cover-crops during this period can potentially also increase soil carbon over time. In discussing the alternative view, they also quote research which indicates that there is little difference, in terms of erosion, between short rotation woody crops and annual crops.

The potential system (based on three to four years between harvests) will result in a system with greater environmental sustainability than the annual harvest of short rotation woody crops. During the programmed three to four years between planting and harvest, and between subsequent harvests, the soil surface is undisturbed. After initial weed control, the full canopy cover achieved will control weed growth, while typically allowing the development of some understory grasses which facilitate surface cover for erosion.

protection. Simpson et al. also note that the use of an under-crop could be beneficial. Cover-crops, such as forage (“pinto”) peanuts, are used in coffee plantations to provide both erosion control and a contribution to the nitrogen supply. Groundcover legume species may be available to offer a complementary strategy for the eucalyptus trees.

The selection process for tree species for short rotation woody biomass production should ensure that the genotypes selected will display vigorous regrowth and coppicing characteristics. This is essential to maximize the rate of regrowth and the life of the crop.

While the harvest operation results in a very high degree of biomass removal, disturbance to the soil surface will be low. Soil compaction will be managed by the matching of tree row spacing with machinery, and high flotation tires would be used on in-field haulage equipment. While grass regrowth will occur and must be managed, it will give further protection to the soil surface.

Simpson also notes that after establishment, short rotation woody crops tend to reduce the leaching of nutrients down the soil profile, relative to annual crops. This is consistent with the findings in low rainfall areas of Australia, where bands of trees are being used to intercept sub-surface flow not utilized by the crop. Significantly, the tree bands have been demonstrated to act as an effective wind break, with the positive effects on crop growth more than compensating for the lost area.

The environmental sustainability of short rotation woody biomass crops can be considered very high.

3.7.6  Option #4 Summary: Tree Crops (including Giant Leucaena and Eucalyptus)

Eucalyptus and giant leucaena have been identified as candidate crops for fiber production on a short rotation basis. Short rotation tree crops have a couple of potential synergies with the current HC&S production system, including the following:

- Suitable for use in areas that are too rocky or otherwise not suited to annually-harvested sugarcane
- If grown in bands across the landscape, the windbreak effect may have a positive impact on the water-use efficiency of the primary crop

By capturing water and nutrients that escape through the crop root zone, downslope water migration can be controlled, while increasing wood yield.
It is anticipated that both eucalyptus and leucaena would be planted in a row configuration, with the row spacing matching the equipment that is utilized for the harvesting operation. While it is not proposed that they would be routinely irrigated, some irrigation initially would increase flexibility with respect to time of planting. The leucaena would be direct planted (utilizing row crop type planters) after a land preparation program similar to that for sugarcane. Cloned seedlings would be used to plant the eucalyptus.

While leucaena is potentially more amenable to a shorter growth cycle, it is proposed that both crops would be grown with a harvest cycle of three to four years. This will reduce the proportion of leaf biomass and increase the proportion of wood biomass, which is of lower moisture content and of lower alkali content. The crops would then be allowed to coppice, with the harvest cycle continuing until the economic life of the stand is reached, the plants removed, and the field replanted.

Matching the harvest cycle length will also allow the same harvesting equipment to be used for both leucaena and eucalyptus tree crops, with the proposed technology being the “over-the-row” harvester which has been developed for Oil Mallee in Australia. This harvester offers the cost advantage of direct harvesting, and has the capability of handling much larger trees than can be harvested by “forage harvester” based systems.

While one advantage of tree crops is that the time of harvest can be manipulated to match product delivery with need, storage will be required. Wood-chip from whole trees will deteriorate unless the leaf fraction is separated. This is best undertaken soon after delivery. The high moisture content leaf material can be used immediately or partially processed, whereas the wood chip can be stored, preferably with aeration.

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185 Generally, short rotation tree crops have a very high energy multiplication efficiency and water-use efficiency, if grown primarily as a non-irrigated crop. And when grown as a non-irrigated crop, the water savings from the areas planted to tree can be utilized to maximize the yield on better cane lands. However, in Central Maui, leucaena and eucalyptus will require irrigation.
The estimated cost of production and harvesting is given in Table 3-35.

<table>
<thead>
<tr>
<th>Area (acres)</th>
<th>5,000</th>
<th>33,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual dry matter tonnage at 8.1 t_{dm}/ac</td>
<td>40,500</td>
<td>267,300</td>
</tr>
<tr>
<td>Annual fresh weight tonnage</td>
<td>90,000</td>
<td>594,000</td>
</tr>
<tr>
<td>Planting cost ($/ac)</td>
<td>$535.00</td>
<td>$535.00</td>
</tr>
<tr>
<td>Annualized planting cost ($/ac) assuming 15 year replant period</td>
<td>$35.67</td>
<td>$35.67</td>
</tr>
<tr>
<td>Annualized planting cost ($/t_{dm})</td>
<td>$1.98</td>
<td>$1.98</td>
</tr>
<tr>
<td>Harvesting and transport cost ($/t, fresh weight)</td>
<td>$22.41</td>
<td>$22.16</td>
</tr>
<tr>
<td>Harvesting and transport cost ($/t, dry matter)</td>
<td>$40.74</td>
<td>$40.29</td>
</tr>
<tr>
<td>Planting and harvesting costs ($/ac)</td>
<td>$864.99</td>
<td>$861.34</td>
</tr>
<tr>
<td>Planting and Harvesting Costs ($/t, dry matter)</td>
<td>$42.72</td>
<td>$42.27</td>
</tr>
</tbody>
</table>

The analysis in Table 3-35 indicates the following.

- The planting and harvesting costs of wood chip is approximately $42 per ton of dry matter.

- If the full cultivated area is planted to trees, the total annual dry matter tonnage will be approximately 267,000 tons.
3.8 Activity 3 Summary

Table 3-36 presents a summary of key parameters relating to the different cropping options, assuming 34,350 acres are utilized for each of the cropping options. The areas available for commercial harvest for each option is the crop production area, less area required for seedcane production.

Key parameters:

- Crop production area is the total area now farmed.
- Annual harvest area is the total farmable area less the area required for seedcane, for either one year crops or two year crops.
- The biomass harvested/acre and total biomass delivered to the mill are on the basis of fresh weight of product and non-crop material delivered per harvested acre.
- Annual land preparation and planting cost are based on estimated costs associated with the actual process for each cropping scenario.
- Harvesting costs are based on the estimated cost per ton X total tonnage for each of the harvesting scenarios, including transport to the mill by adapted versions of the current transport system.
- Other production costs are based on the total cost of crop production indicated by HC&S for the current two year harvest system, less the previously defined land preparation and planting costs and harvesting costs. This cost is assumed to be approximately constant for all crop production systems, and a figure of 25% of this cost is assumed for tree-crops as they will have reduced inputs.
- Total crop production costs are the sum of these costs.
- Tons sugar/year and tons of sugar in molasses/year are based on estimated sugar production and estimated molasses production.
Table 3-36: Summary of key parameters related to different cropping options  
(Assumes 34,350 acres utilized for each of the cropping options)

<table>
<thead>
<tr>
<th></th>
<th>2-year cane</th>
<th>1-year cane</th>
<th>Energy Grass</th>
<th>Trees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burned</td>
<td>Green</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>Crop production area (ac)</td>
<td>35,350</td>
<td>34,350</td>
<td>34,350</td>
<td>34,350</td>
</tr>
<tr>
<td>Annual harvest area (ac)</td>
<td>16,350</td>
<td>16,350</td>
<td>33,700</td>
<td>34,025</td>
</tr>
<tr>
<td>Biomass delivered to factory (t/ac harvested)</td>
<td>107.6</td>
<td>121.9</td>
<td>51.5</td>
<td>62.5</td>
</tr>
<tr>
<td>Total material delivered to mill</td>
<td>1,759,260</td>
<td>1,993,065</td>
<td>1,735,550</td>
<td>2,126,563</td>
</tr>
<tr>
<td>Annual land preparation and planting cost</td>
<td>$13,800,000</td>
<td>$13,800,000</td>
<td>$6,950,000</td>
<td>$4,009,000</td>
</tr>
<tr>
<td>Harvesting and delivery cost</td>
<td>$11,610,000</td>
<td>$17,389,000</td>
<td>$19,459,000</td>
<td>$16,799,844</td>
</tr>
<tr>
<td>Other production costs (irrigation, fertilizer, herbicide)</td>
<td>$27,994,000</td>
<td>$27,994,000</td>
<td>$27,994,000</td>
<td>$27,994,000</td>
</tr>
<tr>
<td>Total crop and harvest cost</td>
<td>$53,404,000</td>
<td>$59,183,000</td>
<td>$54,403,000</td>
<td>$48,802,844</td>
</tr>
<tr>
<td>Tons sugar per year</td>
<td>199,900</td>
<td>190,400</td>
<td>229,710</td>
<td></td>
</tr>
<tr>
<td>Sucrose in molasses (t/year)</td>
<td>19,038</td>
<td>23,788</td>
<td>21,877</td>
<td></td>
</tr>
<tr>
<td>Total sugar per year</td>
<td>218,938</td>
<td>214,188</td>
<td>251,587</td>
<td></td>
</tr>
<tr>
<td>Total energy in sugar (MBTU)</td>
<td>2,782,703</td>
<td>2,722,331</td>
<td>3,197,673</td>
<td></td>
</tr>
<tr>
<td>Tons dry fiber per year (bagasse)</td>
<td>229,700</td>
<td>263,562</td>
<td>232,867</td>
<td></td>
</tr>
<tr>
<td>Tons dry fiber per year (other biomass)</td>
<td>0</td>
<td>96,465</td>
<td>137,159</td>
<td>561,413</td>
</tr>
<tr>
<td>Tons dry fiber per year</td>
<td>229,700</td>
<td>360,027</td>
<td>370,026</td>
<td>561,413</td>
</tr>
<tr>
<td>Total energy in fiber (MBTU HHV)</td>
<td>3,431,718</td>
<td>5,378,803</td>
<td>5,528,188</td>
<td>8,387,510</td>
</tr>
<tr>
<td>Total energy in fiber + sugar (MBTU HHV)</td>
<td>6,214,421</td>
<td>8,101,134</td>
<td>8,725,861</td>
<td>8,387,510</td>
</tr>
<tr>
<td>Energy cost/MBTU</td>
<td>$8.59</td>
<td>$7.31</td>
<td>$6.23</td>
<td>$5.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Total energy in sugar is calculated as the total sugar production times the Higher Heat Value (“HHV”) of sugar, estimated at 12.7 million BTU (“MBTU”) per ton.

• Tons of dry fiber is determined for each of the scenarios. The only fiber source for the current two-year cane is bagasse, whereas for trees and energy grasses it is the only product.

• Total energy from fiber is based on typical values of Higher Heat Value of biomass fiber.

• Total energy in “Fiber + Sugar” is the sum of the energy figures.

• The cost per MBTU of energy produced is the total cost divided by total energy produced.

3.8.1 Analysis of Outputs

On the basis of gross tonnage harvested and delivered, the energy grasses are the highest producers, and they are also the highest producers of dry fiber. It is assumed that the crop selected will be grown to maximize production of fiber. The costs of land preparation and planting, and harvesting and haulage are lower for energy grasses than for comparable sugarcane operations. This is primarily because of the reduced land preparation and planting costs associated with longer production cycles and lower planting rates. The cost of $5.82 per MBTU is a competitive cost relative to sugarcane.

The production of trees gives a lower total energy capture, with the total energy being approximately half of the best sugarcane strategy. The cost per unit energy, at approximately $5.05 per MBTU is the lowest energy cost.

Sugarcane produces a combination of fiber and sugar, each with significantly different energy content and value. The different production and harvesting strategies result in significant differences in both the initial product harvested and in the product recovered. The total energy production from the current two year burned cropping system is approximately 6.2 MMBTU, and the cost is approximately $8.59 per MBTU.

Modifying the cropping system to an unburned harvest, results in a significant increase in total energy at approximately 8.1 MMBTU, with a cost of $7.31 per MBTU. The one year cane option incorporates chopper harvesting and dry trash separation at the mill. Two factors impact on sucrose and energy recovery:
- The increased area harvested because of the reduced seedcane area requirement
- The significant reduction in losses associated with the elimination of the wet cleaning plant

The total energy recovery is anticipated to be 8.7 MMBTU, and the cost of energy is estimated to be $6.23 per MBTU.
End Table 3-1: Summary of sugar losses for Hawaiian crops – 1978 to 1981

<table>
<thead>
<tr>
<th>Plantation</th>
<th>FT-7s No</th>
<th>Field Cane</th>
<th>Cleaning Loss</th>
<th>Prepared Cane</th>
<th>Factory Losses</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bagasse Filt Cake Undeterm. Total</td>
<td>Molasses Sugar total</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.45</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23</td>
<td>17.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>92%</td>
<td>82%</td>
</tr>
<tr>
<td>Kekaha TPA</td>
<td>23</td>
<td>17.32</td>
<td>15.49</td>
<td>1.68</td>
<td>13.81</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>92%</td>
<td>82%</td>
</tr>
<tr>
<td>Olokele TPA</td>
<td>19</td>
<td>19.14</td>
<td>17.48</td>
<td>3.18</td>
<td>14.3</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94%</td>
<td>77%</td>
</tr>
<tr>
<td>McBryde TPA</td>
<td>20</td>
<td>15.52</td>
<td>12.51</td>
<td>2.49</td>
<td>10.02</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>83%</td>
<td>67%</td>
</tr>
<tr>
<td>HC&amp;S (Puunene)</td>
<td>32</td>
<td>18.07</td>
<td>17.33</td>
<td>3.85</td>
<td>13.48</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>99%</td>
<td>77%</td>
</tr>
<tr>
<td>Waialua</td>
<td>14</td>
<td>19.23</td>
<td>17.39</td>
<td>3.91</td>
<td>14.58</td>
<td>0.64</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>93%</td>
<td>72%</td>
</tr>
<tr>
<td>Oahu</td>
<td>39</td>
<td>18.53</td>
<td>16.52</td>
<td>3.96</td>
<td>12.56</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>92%</td>
<td>70%</td>
</tr>
<tr>
<td>DHSC (Haina)</td>
<td>34</td>
<td>18.91</td>
<td>15.74</td>
<td>3.95</td>
<td>11.79</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>86%</td>
<td>64%</td>
</tr>
<tr>
<td>Waialua</td>
<td>20</td>
<td>17.95</td>
<td>13.98</td>
<td>3.56</td>
<td>12.42</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80%</td>
<td>71%</td>
</tr>
<tr>
<td>HC&amp;S (Puna)</td>
<td>19</td>
<td>18.64</td>
<td>16.33</td>
<td>4.06</td>
<td>12.27</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90%</td>
<td>68%</td>
</tr>
<tr>
<td>Kaua'i</td>
<td>31</td>
<td>15.58</td>
<td>13.38</td>
<td>3.36</td>
<td>10.02</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>89%</td>
<td>66%</td>
</tr>
<tr>
<td>Pioneer</td>
<td>18</td>
<td>19.26</td>
<td>16.4</td>
<td>4.76</td>
<td>11.6</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>88%</td>
<td>62%</td>
</tr>
<tr>
<td>Maui</td>
<td>31</td>
<td>22.14</td>
<td>18.89</td>
<td>5.11</td>
<td>13.78</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>88%</td>
<td>64%</td>
</tr>
<tr>
<td>DHSC (Okala)</td>
<td>35</td>
<td>18.30</td>
<td>16.38</td>
<td>4.87</td>
<td>11.31</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>92%</td>
<td>64%</td>
</tr>
<tr>
<td>Punu</td>
<td>25</td>
<td>16.18</td>
<td>14.85</td>
<td>5.9</td>
<td>8.96</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95%</td>
<td>57%</td>
</tr>
<tr>
<td>HC&amp;PC</td>
<td>40</td>
<td>18.84</td>
<td>17.26</td>
<td>6.6</td>
<td>10.66</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94%</td>
<td>58%</td>
</tr>
<tr>
<td>Average</td>
<td>18.24</td>
<td>16.00</td>
<td>4.08</td>
<td>12.03</td>
<td>0.64</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90.4%</td>
<td>68.0%</td>
</tr>
<tr>
<td>Loss % initial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22.4%</td>
<td>4.8%</td>
</tr>
<tr>
<td>Sector Losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24.8%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Sector Recoveries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>75.2%</td>
<td>92.9%</td>
</tr>
</tbody>
</table>

Source: Report of HSPA Ad Hoc Committee on Harvesting, Handling, Wet Cleaning Procedure
Appendix 3-A: Chris Norris

Lead researcher on Activity 3 is Chris Norris of Brisbane, Queensland, Australia. Mr. Norris is an independent contractor to GreenEra, and is a Principal Consultant, Norris Energy Crop Technology. He is internationally-recognized as a leading sugarcane technologist, and has over 35 years of experience in the innovation of agricultural mechanization systems that has been honed over decades of involvement in R&D projects, as well as an extensive understanding of agricultural processes. He is a leader in the Australian Sugar Industry, and has supervised projects ranging from the development of best management practices for current harvesters to fundamental research on losses during billeting, trash separation, and the gathering processes of cane into harvesters. His work has been incorporated in the designs of sugarcane harvesters by major manufacturers. In addition to his expertise in harvesting equipment, he has specialized expertise relating to biomass recovery strategies for cogeneration. In this role, he has worked in the development of optimal solutions for biomass collection for cogeneration and has taken a leading role in the development of trash separations systems. Mr. Norris has consulted globally through internationally recognized consulting and management company Booker-Tate Ltd., including the United States, Uganda, Indonesia, Mozambique, Brazil, Peru, Nigeria, Suriname, Guatemala, Argentina, and the Philippines. He has a Bachelor’s degree in Engineering Agriculture from the University of Southern Queensland, and is a member of the Institution of Engineers Australia, and is a Chartered Professional Engineer. Mr. Norris has authored and co-authored numerous industry related publications.