A Systems Approach for Investigating Water, Energy, and Food Scenarios in East-Central Maui

Carey W. King, Ph. D.

Energy Institute

&

Jackson School of Geosciences

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Executive Summary

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A report of The University of Texas at Austin to the Ulupono Initiative

Carey W. King, Ph.D.

The rain follows the forest (DLNR, 2011). From Hawaii's forest come streams that collect much of this rain, and the water in these streams enables much of the cultural, ecological, and economic value on the islands. Hawaii's future sustainability is linked to its use of water resources. The Island of Maui is certainly no different. In many ways, Maui exemplifies the need for Hawaii residents to consider how they will adapt to climatic and economic changes that originate both from within and from without the Hawaiian Islands.

The world's biophysical and climate systems are changing, in turn pressuring changes for adaptation in human socio-economic systems. Not only in Hawaii, but all over the world there is an increasing need to engage in as many coherent energy, water, and agriculture policies as are possible (King et al., 2013). Constraints in water resources can easily translate to constraints in energy and food production. To ensure Maui's long-term prosperity it is crucial to resolve Maui's societal conflicts focused on water. This report exists to provide information to the people of Hawaii such that they can facilitate further discussion as to their desired use of water in the context of a sustainable future for Hawaii.

This report seeks to inform actions for Hawaii's sustainable water use in agriculture on East Maui using a *systems approach*. This systems approach considers water as available for multiple purposes to consider how Maui's water resources can be used to achieve multiple sustainability objectives. From a water perspective, sustainability is narrowly defined as not drawing on groundwater beyond maximum sustainable yield. This report explicitly does not address the litigation issues related to instream flows and native uses of water. Ulupono commissioned this report to address the following questions:

- Is the current use of energy and water for agriculture sustainable?
- Do we have enough water to meet society's goals of increased local food and renewable energy production without causing unintended consequences?
- How much food and electrical and fuel energy can we produce from the East Maui watershed while sustainably stewarding our water resources?
- What are the impacts to the broader Maui water and energy systems?
- What do we know about how much can water supply be increased through watershed management and restoration and at what cost?

System Scenarios

The analysis described in this report focuses on ***the water and energy inputs and outputs for producing both biofuel feedstocks in the Central Plain of Maui and food crops in Upcountry Maui***. The system water, food, and energy scenarios in this report are based upon the idea that Maui's water supplies are becoming increasingly constrained due to changes in climate, increasing native and visitor populations, and movements and legal rulings to reduce water diversions from streams for both environmental and native cultural reasons (e.g. taro farming).

The water availability for different scenarios is based upon the precipitation, surface water, and groundwater on the Eastern (Haleakala) portion of Maui. Most of the 330 million gallons per day (MGD) of average surface water runoff is already used for some purpose (see **Figure E-1**). While there appears to be a large amount of groundwater resource available, the costs are prohibitive for accessing the bulk of that water. Many new water supplies such as more pipelines, groundwater wells, reclaimed water facilities, and desalination are constrained by the available capital required to invest in new fresh and potable water sources. There is some opportunity to reclaim more wastewater that is already being reclaimed. Two strategies (i) increased water conservation and demand management and (ii) increased wastewater treatment for reclaimed water use, have been determined to be the most promising options for matching Maui potable water demand with supply (see Section 3.2 and (DWS, 2010)).

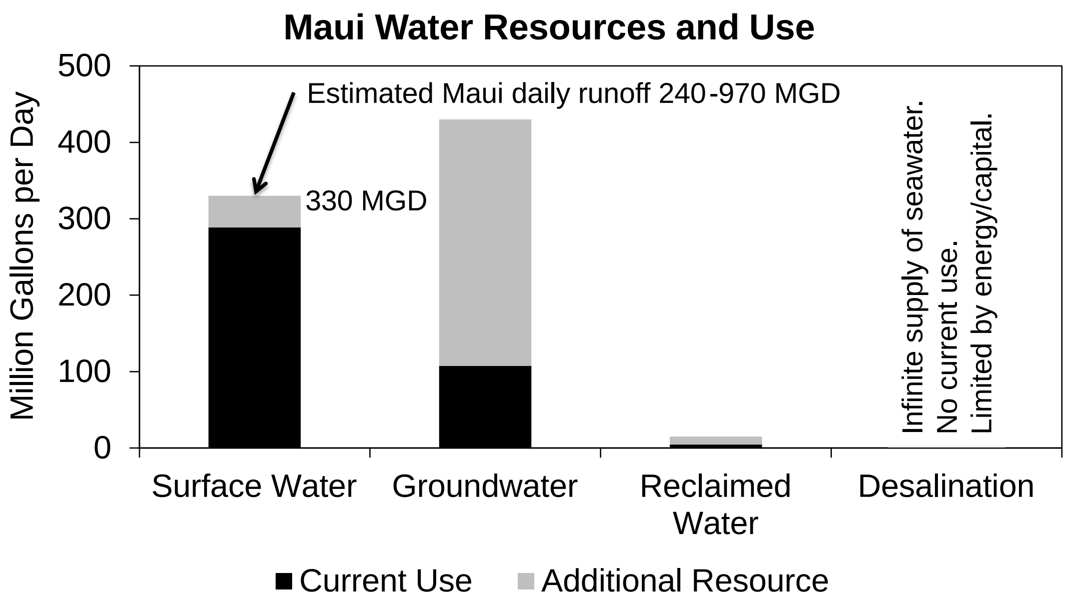

Figure E-1. Approximately 400 million gallons of water per day (MGD), on average, are used for irrigation and municipal supply on Maui. Reclaimed water potential supply from treated wastewater is ~15 MGD, and 20-30% of wastewater is in current use (Wastewater Community Working Group 2010). An estimated 330 million gallons of surface water are available for use each day (Kinoshita and Zhou 1999, Table 3-1). East Maui Irrigation capacity = 445 MGD. 10-40% of 70 in/yr of rain becomes surface water of ~240-970 MGD (Gingerich and Oki, 2000).

The scenarios presented in this report are structured to provide insight into the following questions about water, energy, and food on Maui:

- How does a smaller crop footprint (e.g. land use) for sugar cane relate to water use, groundwater sustainability, and yield?
- How much liquid biofuel can be produced from sugar cane, or other bioenergy feedstocks, in Central Maui?
- How do alternative biofuel crops compare in terms of water consumption?
- How much water and land are needed to grow a significant share of locally-consumed meat, dairy, fruits, and vegetables for Maui?
- How does a 'systems' combination of crops for biofuels and food relate to surface water use, groundwater sustainability, and broader sustainability goals for Hawaii and Maui?

The scenarios begin with a "calibration" scenario that models the current 'water-deficit' irrigation situation as described by Hawaiian Commercial and Sugar (HC&S) in Exhibit G-1 of (CWRM, 2010).

This calibration scenario verifies that the model can represent today's practice. Then, alternative scenarios are simulated on a smaller total crop footprint of 23,000 acres in Central Maui (eastern side) instead of the current 30,000 acres. Three alternative biofuel crops are modeled: sweet sorghum, cassava, and banagrass.

In addition to the biofuel scenarios, two food production scenarios are included. One food scenario is based on a concept of irrigated pasture for grass-fed cattle to produce both beef and milk (or other dairy products). *Milk and beef production serve as proxy indicators* for output of consumer products from use of pasture land. The second food scenario is for fruit and vegetable production, or "diversified agriculture". Thus, the food scenarios present one of many possible ways to utilize land on Maui for diary, protein, and fruit and vegetables. The scenarios are defined as follows:

Calibration – 30,000 acres sugar cane, water deficit: The calibration scenario assumes approximately 30,000 acres of sugar cane grown on current HC&S land using the average irrigation from Exhibit G-1 of (CWRM, 2010). Results are calculated for sugar and molasses production.

Scenario 1 – 30,000 acres sugar cane, full water: This scenario is the same as the calibration scenario, except groundwater pumping is increased to deliver the full water needs to the sugar cane crop. Results are calculated for ethanol production.

Scenario 2 – 23,000 acres sugar cane, full water: This scenario is a reduced footprint for sugar cane production to compare the water and yield to the calibration scenario and Scenario 1. Results are calculated for sugar and molasses production (Scenario 2s) and ethanol production (Scenario 2e).

Scenario 3 – 23,000 acres sweet sorghum, full water: This scenario is to compare sweet sorghum biofuel production and water needs to that of other biofuel crops.

Scenario 4 – 23,000 acres cassava, full water: This scenario is to compare cassava biofuel production and water needs to that of other biofuel crops. Two cassava yields are assumed: a 'standard' cassava yield (Scenario 4s) representative of existing commercial production, and an 'improved' higher cassava yield (Scenario 4i) believed possible by Ulupono Initiative.

Scenario 5 – 23,000 acres banagrass, full water: This scenario is to compare anticipated banagrass biofuel production and water needs to that of other biofuel crops.

Scenario 6 – 5,850 acres pasture: This scenario models beef and milk production from grass-fed cattle in Upcountry Maui.

Scenario 7 – 1,000 acres diversified agriculture: This scenario models fruit and vegetable production in Upcountry Maui.

Scenarios 8 – System energy and food scenarios: These four 'system' scenarios combine the results for Scenarios 6 and 7 to each of the biofuel Scenarios 2, 3, 4, and 5.

Water Resource Sustainability

In considering multiple uses of water on Maui, one measure of water resource sustainability is the balance of groundwater extraction and recharge. To use an aquifer sustainably, one must not continually extract more water from an aquifer than seeps in from rainfall and irrigation. The Department of Land and Natural Resources has established sustainable aquifer yields to help manage groundwater use (Wilson Okamoto Corporation, 2008).

As shown in previous studies, the irrigation of sugar cane in Central Maui enables groundwater extraction higher than that of the sustainable yields of the Kahului (1 million gallons per day, MGD, or 0.4 billion gallons per year, BGY) and Paia aquifers (7 MGD, or 2.5 BGY) because the surface irrigation water from the East Maui Irrigation system effectively recharges the aquifers. The leftmost results in Figure E-2 show that while 19 BGY of water is extracted to irrigate sugar cane, there is 18 BGY of recharge, leaving a net groundwater extraction of 1 BGY or less. However, the results of Scenario 1 show that irrigating the same 30,000 acres of sugar cane to fulfill all crop water needs creates a substantial net water depletion of 13 BGY due to the same quantity of East Maui Irrigation (EMI) system surface water but much more groundwater extraction (35 BGY). This result reinforces why, in an average rainfall year, 30,000 acres of sugar cane in Central Maui cannot be sustainably fully irrigated.

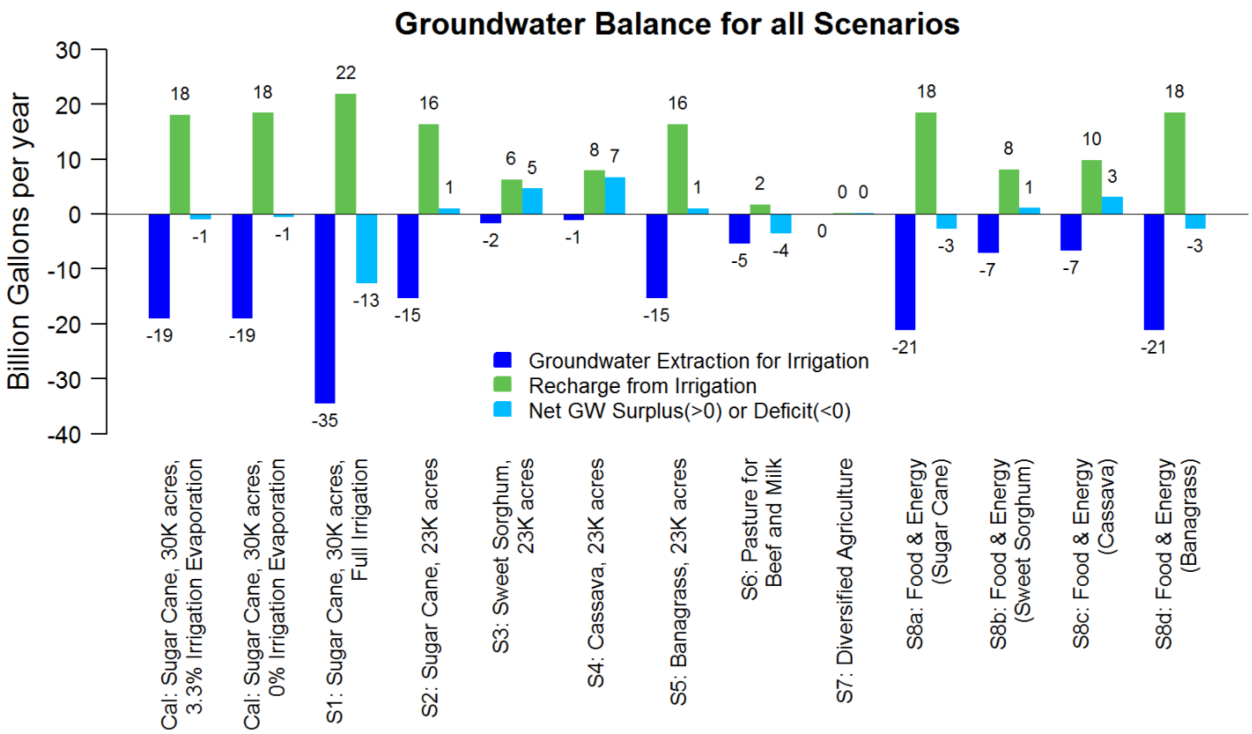

Figure E-2. The groundwater extraction, recharge from irrigation, and net groundwater extraction provide summary metrics to compare the groundwater sustainability of all scenarios. Plotted values assume average monthly rain and EMI ditch flows. Numbers might not add due to rounding.

Scenarios 2–5 show that growing biofuel crops on 23,000 acres in Central Maui enables full irrigation of each candidate crop while maintaining aquifer sustainability. Fully irritating 23,000 acres of sugar cane (Scenario 2) provides approximately the same total biomass yield as the current practice of partially irrigating 30,000 acres (calibration scenario). Growing cassava and sweet sorghum requires much less water, although the assumption of less water for sweet sorghum corresponds to a relatively low yield for Hawaiian conditions. The 5,850 acres of pasture in Upcountry Maui for intense beef and milk production would require significant irrigation (5 BGY), assumed to come solely from groundwater. The irrigation requirements for 1,000 acres of diversified agriculture are minimal compared to the other crops.

The four combined energy and food 'system' scenarios show net groundwater extraction that is either positive or well below the estimated sustainable yields for Central Maui and Upcountry aquifers (Paia, Kahului, and Makawao).

Energy and Food Sustainability

The energy and food production of the four 'system' scenarios can be viewed as relative to the total Maui consumption for those products. Figure E-3 shows how each of the system scenarios compare to the present "calibration" scenario of 30,000 acres of sugar cane for sugar. Each system scenario has the same production of milk (100% of Maui consumption), beef (41% of Maui consumption), and fruits and vegetables (69% of Maui consumption). The amount of gross electricity generated from renewable energy includes the biomass generation from the biofuel feedstocks as well as existing wind and hydropower generation on Maui. The renewable generation on Maui is now dominated by wind power, and all renewable sources range between 22% and 28% of the gross electricity generation on the island.

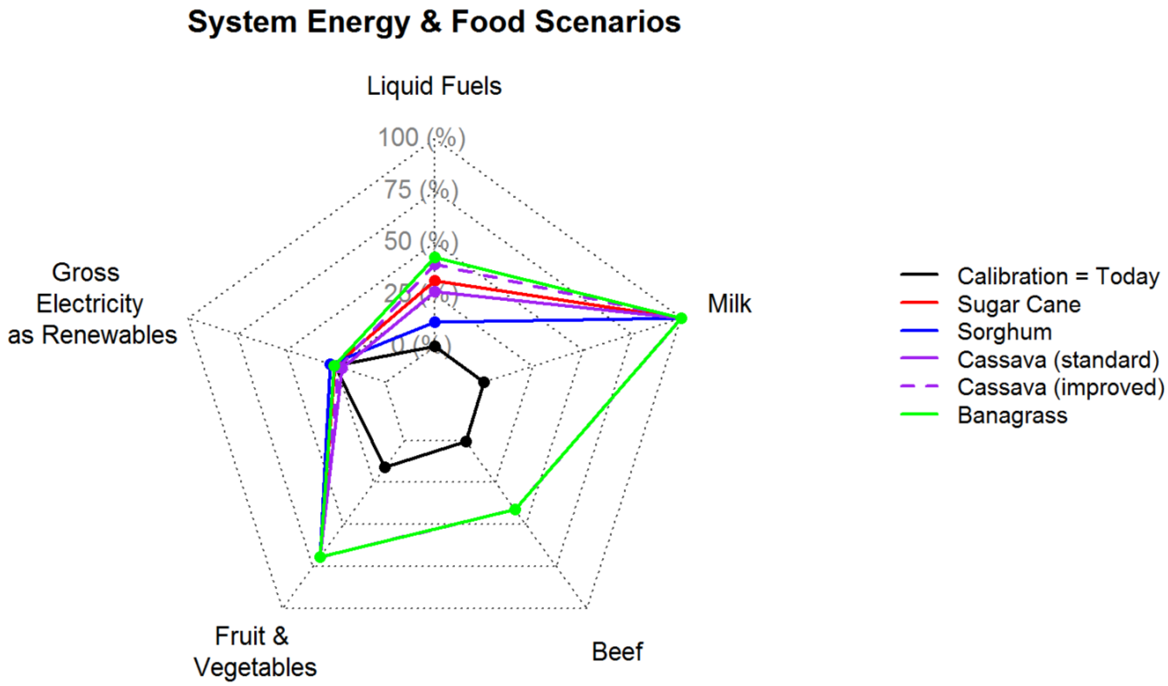

Figure E-3. Maui production relative to consumption for each of five metrics for the combined 'system' energy and food scenarios. All 'system' energy and food scenarios, by their definition, meet the same percentage of local milk, beef, and fruits & vegetables. The calibration scenario representing today's situation produces much less food and no biofuel.

The amount of liquid biofuels, ethanol in all cases, varies considerably among the scenarios. The percentage of liquid fuels is calculated as the energy content in ethanol divided by the energy content of Maui's gasoline consumption. Very little biofuel (12%) can be produced from sweet sorghum when assuming the low yields from recent Hawaii crop trials (Hashimoto, 2012, Hashimoto et al., 2012)). More extensive crop trial information is needed to verify if sweet sorghum can be grown in Hawaii with the same yields as non-tropical regions. Twenty-three thousand acres of sugar cane converted to ethanol could produce 32% of Maui's gasoline energy consumption, and approximately 43% could be produced from banagrass (using cellulosic materials). Ethanol production from cassava could range from 26% to 40% of Maui gasoline energy consumption depending upon how much the cassava yield could be increased from known 'standard' yields.

The water balance calculations were repeated when assuming the low ditch flow year of 1962 in which the EMI ditch system delivered approximately 28% less water than an average year. In this "drought" scenario the 23,000 acres of cassava is still modeled to have net groundwater recharge even when applying full irrigation. The 23,000 acre sugar cane and banagrass scenarios would operate at a substantial net loss of groundwater of 16 BGY relative to a 1 BGY net gain in an average ditch flow year.

Conclusion

Overall, there is a significant opportunity to meet multiple sustainability goals using the same or a lesser quantity of water for large-scale farming of biofuel crops in Central Maui. These multiple goals include more local food, increased renewable energy, and sustainable groundwater usage. Maui can create triple the economic value is gets from each gallon of water used in agriculture, while consuming one third less water than Central Maui uses today.

If less surface water is needed for agriculture in Central Maui, then 'newly available' surface water could be used for irrigating other lands for food production, the water could remain in streams for purposes of enhancing biodiversity cultural uses of water, and/or the water could be available to deal with potential reductions in future rainfall. The status quo agriculture in Central Maui currently operates at a water deficit with today's average rainfall patterns, but Hawaiian rainfall has been decreasing at a rapid rate the last few decades. These declines in rainfall are consistent with expectations from rising temperatures from climate change. Thus, there is the distinct possibility that Hawaiian rainfall will continue to decrease in the future. More drought-tolerant and less water-hungry crops are likely to be needed if only to deal with decreased rainfall, and increased water demands for municipal uses. By thinking systematically about water use on the island in short and long terms, Maui stakeholders have the potential to proactively adapt to a changing world such that they protect their most important and valuable resources.

More scientific and commercial research will be needed to definitively characterize the opportunities highlighted in this report before commercial agricultural companies or government could be confident in making the investments needed to change course. The critical needs for scientific and commercial research are:

- Watershed management and restoration to understand costs and hydrological impact
- Aquifer characterization, particularly for the major aquifers affected by ground water pumping and possible
- Pre-commercial bioenergy crop trials on cassava at the scale needed to affirmatively determine yield and harvest requirements
- Integration analysis of use of curtailed wind energy for water pumping in agriculture and municipal systems

If the same cooperative support from the Maui stakeholders that made this report possible extends to the next phase of inquiry, we are confident that Maui can realize the opportunities they collective have.

A Systems Approach for Investigating Water, Energy, and Food Scenarios in East-Central Maui

A report of The University of Texas at Austin to the Ulupono Initiative

Carey W. King, Ph.D.

1. Introduction

The rain follows the forest (DLNR, 2011)[1]. From Hawaii's forest come streams that collect much of this rain, and the water in these streams enables much of the cultural, ecological, and economic value on the islands. Hawaii's future sustainability is linked to its use of water resources. The Island of Maui is certainly no different. In many ways, Maui exemplifies the need for Hawaiia residents to consider how they will adapt to climatic and economic changes that originate both from within and from without the Hawaiian Islands.

Maui has locations that are some of the wettest and driest places on Earth. Maui's desert regions (leeward areas) receive an average of less than 400 millimeters of rain per year, similar to the Sonoran Desert. Yet just an hour's drive away lies Pu'u Kukui in Mauna Kahalawai (the West Maui Mountains) where some locations collect more than 9,000 millimeters of rainfall per year, about three times as much as the Amazon. For a relatively small island, these contrasts in precipitation are staggering — and the disparity is the source of both significant benefits and significant conflicts on Maui. Agriculture and tourism are Maui's major economic activities; both depend on water, but they tend to have opposing water needs. Agriculture depends (and has depended) on redistributing water resources from streams to current (and former) plantations around the island. Meanwhile, tourism greatly benefits from ample flows in the streams and waterfalls that have made Maui famous.

Maui's cultural heritage also factors into water allocations. The relatively recent (last two centuries) plantation culture that is enabled by large-scale water transfers conflicts with the centuries-old native culture that deeply identifies with and depends on water remaining in its natural setting. As Hawaii plantation agriculture has lost economic competitiveness over the last few decades, particularly sugar cane production, lawsuits have arisen over how to use water once diverted for crops. The declining availability of water — due to macro-scale precipitation cycles perhaps related to climate change — exacerbates these pressures, putting different sectors of society at odds with each other.

The world's biophysical and climate systems are changing, in turn pressuring changes for adaptation in human socio-economic systems. Not only in Hawaii, but all over the world there is an increasing need to engage in as many coherent energy, water, and agriculture policies as are possible (King et al., 2013). Constraints in water resources can easily translate to constraints in energy and food production. This report presents a systems view of water and energy use in East-Central Maui to continue the discussion of how to view the use of water resources.

1.1 Report focus and context

To ensure Maui's long-term prosperity it is crucial to resolve Maui's societal conflicts focused on water. This report exists to provide information to the people of Hawaii such that they can facilitate further discussion as to their desired use of water in the context of a sustainable future for Hawaii. For many, a future sustainable Hawaii includes reducing consumption of oil, arguably the world's most

[1] http://hawaii.gov/dlnr/rain

valuable primary energy resource. Hawaii is dependent on oil for both transportation and electricity production, and there are viable renewable electricity technologies, particularly wind turbines, photovoltaic panels, and solar hot water systems, that can reduce the use of oil products for electricity and hot water. In addition to using electricity as an energy carrier for transportation (e.g. electric cars), liquid biofuels, such as ethanol, can substitute for gasoline in cars and trucks. But because biofuels are derived from crops that need water, it takes much more water to drive a mile on biofuels than it does on gasoline (Gerbens-Leenes et al., 2009, King and Webber, 2008).

This report seeks to inform actions for Hawaii's sustainability. There are many definitions of the word *sustainability* as related to issues of economy, the environment, and social relationships. The Hawaii 2050 Sustainability Plan was created by the Hawaii 2050 Sustainability Task Force during a 2-year citizen and stakeholder engagement process (Hawaii, 2008). This report for the Ulupono Initiative is relevant to four of the five specific goals of the Hawaii 2050 Sustainability Plan:

- Living Sustainably is part of our daily practice in Hawai`i.
- Our diversified and globally competitive economy enables us to meaningfully live, work and play in Hawai`i.
- Our natural resources are responsibly and respectfully used, replenished and preserved for future generations.

Of the priority actions for 2020 listed in the Hawaii 2050 Sustainability Plan, this present report informs possibilities to make progress on five of nine of these actions:

- Reduce reliance on fossil (carbon-based) fuels.
- Develop a more diverse and resilient economy.
- Create a sustainability ethic.
- Increase production and consumption of local foods and products, particularly agriculture.

Unfortunately, Hawaii's future might be drier than its past. Rainfall has been experiencing a decreasing trend over the last several decades (see Figure 1), and if this trend continues, there can be significant negative consequences for Hawaiian Islands (Diaz and Giambelluca, 2012, Frazier et al., 2011). To date, there has already been considerable research investigating the climatic influences on short and long-term Hawaii rainfall, and Pacific Ocean cycles such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) show correlations with many wet and dry periods (Diaz and Giambelluca, 2012, Frazier et al., 2012). There is evidence that rising global temperatures could reduce Hawaii precipitation (Diaz et al., 2011, Frazier et al., 2011, Giambelluca et al., 2008). One potential mechanism could be a rise in average cloud heights, or lifting condensation level (observed over the last decade), combined with a stronger trade wind inversion that makes clouds shorter (Diaz et al., 2011). These higher and shorter clouds reduce orographic rainfall because of a narrowing of the cloud contact height with mountain slopes. In addition, climate change might be causing a reduction in the frequency of northeasterly trade winds that are preferential for the islands to collect orographic rainfall, particularly on northeastern Maui (personal communication, Victoria Keener). Ongoing research is attempting to validate these hypotheses.

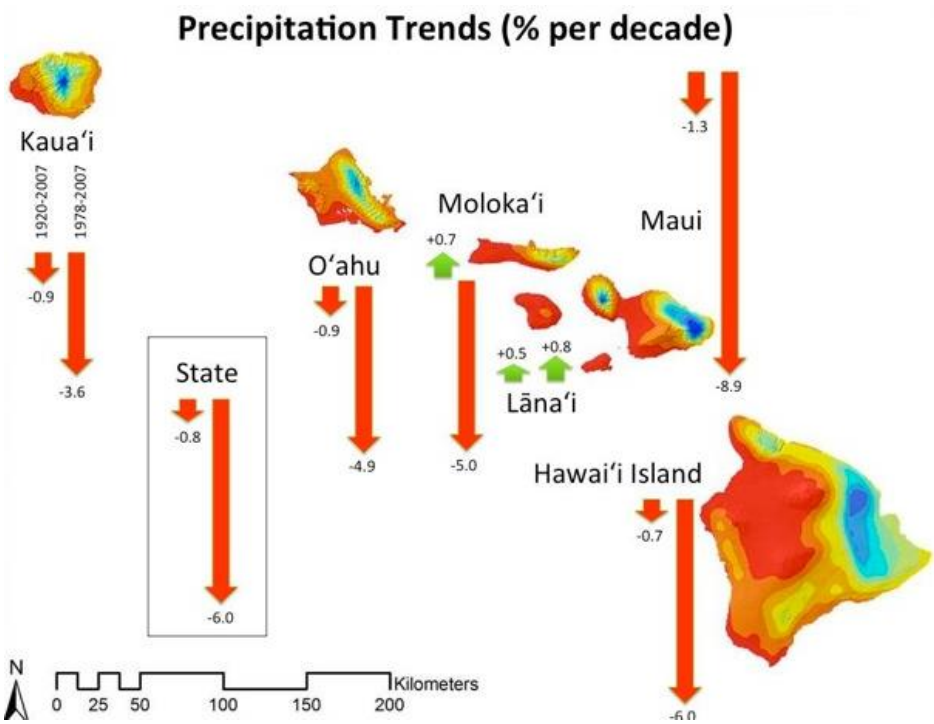

Figure 1. There has been a significant *increase in the rate of change* of *decreasing precipitation* in Hawaii since 1980 as compared to the overall trend from 1920–2007. This image is courtesy of Abby Frazier and Tom Giambelluca from their work as part of the Hawaii Rainfall Atlas (Frazier et al., 2011, Giambelluca et al., 2013).

The analysis described in this report focuses on ***the water and energy inputs and outputs for producing both biofuel feedstocks in the Central Plain of Maui and food crops in Upcountry Maui***. Agriculture consumes over 90% of human water use on Maui (see Section 2.2.1.3). In this sense, the water availability for different scenarios is based upon the precipitation, surface water, and groundwater on the Eastern (Haleakala) portion of Maui. Most of the 330 million gallons per day (MGD) of average surface water runoff is already used for some purpose (see Figure 2). While there appears to be a large amount of groundwater resource available, the costs are prohibitive for accessing the bulk of that water. There is some opportunity to reclaim more wastewater that is already being reclaimed. The two strategies of increased water conservation and demand management together with increased wastewater treatment for reclaimed water use are the most promising options for matching Maui water demand with supply (see Section 3.2 and (DWS, 2010)).

While the analysis of this report focuses on crop and biofuels production, the results should be placed in the context of the local water availability and demands for other purposes: instream flows for Native Hawaiian culture, biodiversity, and municipal water. The focus on East and Central Maui implies no particular restrictions for either the eastern, central, or western portions of Maui. The analysis is one of scenarios, and a similar scenario analysis could be done for the rest of Maui and other Hawaiian Islands.

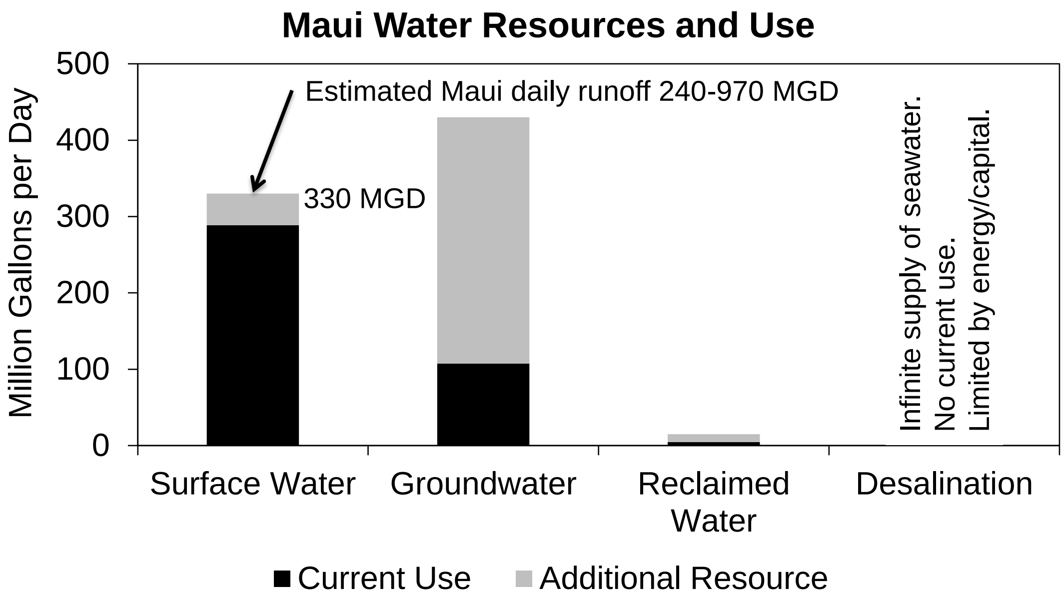

Figure 2. Approximately 400 million gallons of water per day (MGD), on average, are used for irrigation and municipal supply on Maui. Reclaimed water potential supply from treated wastewater is ~15 MGD, and 20-30% of wastewater is in current use (Wastewater Community Working Group 2010). An estimated 330 million gallons of surface water are available for use each day (Kinoshita and Zhou 1999, Table 3-1). East Maui Irrigation capacity = 445 MGD. 10-40% of 70 in/yr of rain becomes surface water of ~240-970 MGD (Gingerich and Oki, 2000).

1.1.1 *Vision of Ulupono Initiative*

Ulupono uses a systems approach to understand how partners and projects work together to create the most impact. Ulupono Initiative strives to improve the quality of life for the people of Hawaii by investing in Hawaii-focused businesses and organizations. Ulupono knows that making an impact in their key mission areas of food, energy and waste will help achieve a vision for a more self-reliant community. Ulupono Initiative invests in innovative organizations to fuel change focusing on helping transform the Hawai'i community and the lives of Hawaii citizens. Ulupono Initiative investments span both the for-profit and non-profit sectors to ensure support for strong ideas that will catapult Hawai'i toward greater self-sufficiency. For more information visit the Ulupono Initiative website (www.ulupono.com).

1.1.2 *Stakeholder engagement*

During the multi-year investigations supporting the analysis in this report, the author and Ulupono Initiative representatives met with many Hawaii knowledge experts and stakeholders. During the research for this study, the author presented the scenario analysis concept and/or preliminary results to some of the following stakeholders to receive comments and feedback. This list of stakeholders in no way implies the endorsement or verification of the findings or conclusions of this report by any of the listed organizations or individuals as the findings and conclusions are solely those of the author.

1.1.2.1 Private businesses, individuals, and non-governmental organizations

Hawaiian Commercial and Sugar: The University of Texas at Austin research team first met with representatives of HC&S in 2010, and HC&S employees responded to questions through the project period into May 2013. During 2010, HC&S representatives took the team on an extensive tour of their agricultural lands, irrigation system, and sugar production facility. The author greatly appreciates the facilities tour, information exchange, and provided perspectives of the last

sugar cane plantation in Hawaii. Specific appreciation is given to Lee Jakeway, Mae Nakahata, Garret Hew, Rick Volner, and Christopher Benjamin.

Earth Justice: From the beginning of this project, Isaac Moriwake and Kapua Sproat provided valuable insight into the local context of water allocation issues in Hawaii. Isaac and Kapua directed the team to learn the cultural practice of taro farming at Ka'ala Farms to better understand the role of traditional farming in Hawaii and its role in a modern Hawaii. Isaac also provided feedback on preliminary results of the scenario analysis during Spring 2013.

Carl Freedman: The University of Texas at Austin research team met with Carl at the beginning of the project in 2010, and his background information on Maui's water supply and systems is valuable. Further, his subsequent work for Maui County on water planning and supply options provides a wealth of data.

Hawaii Community Foundation: The author and Ulupono Initiative representatives presented preliminary scenario analysis results to Josh Stanbro during the Spring of 2013. Josh provided valuable feedback and discussed the context of this report with regard to the Foundation's Fresh Water Initiative. The author hopes that this report can help serve the needs of HCF's Fresh Water Initiative as well as other similar stakeholder engagement efforts in Hawaii.

Jonathan Likeke Scheuer: The University of Texas at Austin research team met with Jonathan at the beginning of the project in 2010. In addition to providing the team with valuable insight and background knowledge into the history of land and water use in Hawaii, Jonathan directed the team to specific locations on Maui to learn and see for ourselves the stream water diversions that are at the center of many water allocation disputes.

The 'Aina Institute: The author learned much about the history of Hawaii biofuels research and development from Bob Shleser. Bob also provided feedback and support on the general approach of the analysis presented in this report.

Maui Economic Development Board: The University of Texas team met with representatives of MEDB at the beginning and end of this project. Specific appreciation for feedback and important considerations go to Jeanne Skog, John Harrison, and Frank De Rego. The author appreciates the stakeholder engagement work of MEDB and looks forward to this report, and the underlying model, as being informative and useful for future MEDB community engagement efforts.

Hawaii Bioenergy Institute: During a presentation of preliminary scenario results in the Spring 2013, Kyle Barber and Scott Shibata provided valuable feedback to the author and Ulupono Initiative on how to compare and present information on different scenarios. They also provided feedback on some of the underlying parameters governing model outputs.

The Nature Conservancy: The author and Ulupono Initiative presented preliminary results to TNC during Spring 2013. TNC provided valuable feedback on what is and is not known regarding the role of invasive species reducing water supplies in rainsheds of Hawaii, specifically the northeast (leeward) side of East Maui. Specific appreciation goes to Mark Fox, Stephanie Tom, Jody Kaulukukui, and Mark White.

1.1.2.2 State agencies

Commission on Water Resources Management, Department of Land and Natural Resources, State of Hawaii: An important subset of data used in this report is due to actions and reporting by the CWRM. The author and Ulupono Initiative met with CWRM representatives in the Spring 2013 to discuss preliminary results and presentation of the results. Specific appreciation is given to William Tam, Lenore Ohye, and Dean Uyeno.

Hawaii Department of Agriculture, State of Hawaii: The author and/or Ulupono Initiative met with Hawaii DOA employees multiple times during the project period to get feedback on agricultural scenarios. The insights and feedback from the DOA, particularly Director Russell Kokubun, helped guide the analysis and scenarios definitions. Specific appreciation is also given to Scott Enright and Earl Yamamoto.

Hawaii Office of Planning, State of Hawaii: Jesse Souki in the Office of Planning provided insight into the history of water allocation and development issues in Hawaii as well as information and data resources.

1.1.2.3 Academic and scientific research (state and federal)

College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa: Multiple meetings and exchanges with faculty and research staff at CTAHR provided invaluable information and feedback for this project. Much of the existing knowledge of Hawaii food and biofuel feedstock crop development is due to the continuous research and development efforts within CTAHR. This present report could not have produced the range of scenarios without the publications and feedback from CTAHR faculty and staff. Specific appreciation goes to Charles Kinoshita, Carl Evensen, Richard Ogoshi, and Ali Fares for providing information and feedback on some of the underlying parameters governing model outputs presented in this report.

Department of Geography, University of Hawaii at Manoa: If you ask about water resources in Hawaii, all roads point to Tom Giambelluca. Specific appreciation goes to Tom and his student Abby Frazier for providing data on monthly rainfall patterns on Maui that were used in the modeling for this report. Further, the online resources of the Hawaii Rainfall Atlas (http://rainfall.geography.hawaii.edu/) provide stakeholders and researchers easy access to valuable data on Hawaii precipitation patterns.

Hawaii Natural Energy Institute, University of Hawaii at Manoa: Preliminary scenario results were presented to Scott Turn in the Spring 2013, and the author appreciates his feedback and insight into energy-related issues and history on Hawaii.

U.S. Department of Energy: In Spring 2013 the author and Ulupono Initiative presented preliminary scenarios results to James Spaeth, a DOE Senior Advisor for the Pacific Region. Jim's perspectives on presentation of the results have proven useful in the preparation of this report.

East-West Center, Pacific Regional Integrated Sciences and Assessments (RISA) project: Preliminary results were shown to Victoria Keener to compare to the goals of the Pacific RISA project with regard to understanding impacts of climate change to Hawaii.

United States Geological Survey: The University of Texas at Austin team corresponded with USGS representatives several times over the course of the project. The streamflow and irrigation ditch

flow data were crucial to the analysis of scenarios in this report. During meetings and via e-mail, the USGS researchers and staff provided valuable feedback and suggestions for analysis. Specific appreciation goes to Stephen Anthony, Steve Gingerich, Delwyn Oki, and Ronald Rickman.

United States Department of Agriculture: The reporting of Hawaii agricultural yield data is crucial for using those data for scenario analyses such as in this report. Specific appreciation goes to Mark Hudson for helping the author access and interpret the agricultural data that he maintains for the State of Hawaii on behalf of USDA.

1.2 Model Description

The purpose of the model used for this analysis is for high level analysis of planning scenarios. The model uses the STELLA[2] software platform to track input water flows from rainfall, surface water irrigation ditches, and groundwater wells and output water flows from land use and irrigation practices. The water output flows are crop evapotranspiration, irrigation needs, aquifer recharge, and excess water that is not 'consumed' by growing crops. However, the model is not a physics-based model (e.g. it does not use climate conditions together with heat and water budgets to estimate crop water use and crop yield) and cannot inform specific irrigation scheduling needs for operational purposes. Because the model is not physics-based, there are many data that are necessary inputs to make the model informative. For example, necessary data are monthly reference evapotranspiration for the land parcels of interest.

The model runs on monthly time steps in order to capture important seasonal patterns in rainfall and surface water availability. The model focuses on high level scenarios rather than detailed operational procedures. The Appendix describes the specific model input parameter values and assumptions. For a full description of the model inputs, outputs, calculations, and assumptions, refer to the separate report from The University of Texas at Austin to Ulupono Initiative entitled: *Description of Model for Investigating Land, Water, Energy, and Food Scenarios in Hawaii*.

1.3 Data Sources used in Model

The analysis presented in this document is possible only because the relevant input data exist. In turn, these data exist because of the countless hours of work and dedication from federal, state, and local government agencies as well as educational institutions and private businesses. Both the author and Ulupono Initiative are indebted to the researchers and organizations that have made these data available via past recording and reporting. These available data originate from scientific studies, measurement systems, and documents related to legal proceedings. The remainder of this section discusses the primary sources of data and data used form these sources. Specific input data and mathematical methods are listed in the Appendix of this report.

1.3.1 State of Hawai`i

The project used geographic information systems (GIS) files for Hawaii geography and land use as obtained from the state Office of Planning website: http://planning.hawaii.gov/gis/. These files were used to define the size and shape of the land parcels used in the scenario analysis. The land parcels were chosen based upon a subjective tradeoff of several factors: size (2,000-5,000 acres), single owner, overlying over a single aquifer, similar climate and/or land use potential, and access to surface irrigation ditches.

[2] http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx

Several documents of the Hawai'i Department of Land and Natural Resources (DLNR) Commission on Water Resources Management (CWRM) were very useful in providing input information to the model used in this report. Specifically informative was the Compilation of Data Submissions, Part II (PR-2010-01) in May 2010 that includes information submitted and assessed in the reconsideration of interim instream flow standards for 16 surface water hydrologic units on the northeast side of Maui island (CWRM, 2010). The information provided by Hawaiian Commercial and Sugar (HC&S) made it possible to include some practical details (water deliveries; water seepage or infiltration; groundwater pump capacities, typical operation, and location) about the irrigation system on much of land being modeled in this study.

1.3.2 Maui County

Data on the municipal water supply is included in the model to ensure perspective on how the quantity of water for agriculture compares to that for domestic use. The Maui Department of Water Supply (DWS) website (http://www.co.maui.hi.us) provides timely updates on the monthly water production for their system.

1.3.3 United States Geological Survey

Two USGS publications were particularly valuable in providing context and information on the water supply and water balance on East and Central Maui:

- Effects of Agricultural Land-Use Changes and Rainfall on Ground-Water Recharge in Central and West Maui, Hawaii, 1926-2004 (Engott and Vana, 2007), and
- Median and Low-Flow Characteristics for Streams under Natural and Diverted Conditions, Northeast Maui (Gingerich, 2005).

Additionally, this report used USGS historical stream gauge data of mean monthly flow rates within streams and the irrigation ditches. The mean monthly ditch flows for the Wailoa ditch flow come from the USGS stream gauge database for gauge number 16588000 at Honopou stream near Huelo, Maui. Annual mean flow data were also obtained for New Hamakua ditch (USGS gauge: 16589000), Lowrie ditch (USGS gauge: 16592000), and Haiku ditch (USGS gauge: 16594000).

1.3.4 University of Hawai'i at Manoa

Over the past several decades, students, faculty, and researchers at The University of Hawaii have produced numerous scientific papers, reports, and databases that provide valuable information on the natural resources of Hawai`i. Several of these works were crucial in providing data and insight for input into this report.

The data within the Hawaii Rainfall Atlas (http://rainfall.geography.hawaii.edu/) was used to estimate monthly rainfall for each land parcel in the model. This database, run by the Geography Department of the University of Hawaii at Manoa, is extremely valuable for characterizing the rainfall patterns across the Hawaiian Islands. Rainfall data used in this project originated from the Rainfall Atlas online resource as well as GIS files that were provided by Dr. Tom Giambelluca and Abby Frazier.

The Hawaii Bioenergy Master Plan, prepared by the Hawaii Natural Energy Institute, is a tremendous intellectual resource that provides good background data on bioenergy crops and relevance to the Hawaii situation (HNEI, 2009).

The Hawaii Agricultural Water Use and Development Plan, produced by the College of Tropical Agriculture and Human Resources to the Hawaii Department of Agriculture, presents a wide array of information including crop planting time and known irrigation practices for crops in Hawaii.

Although this present report does not focus on the rainshed and benefits of native forest cover to capturing water from precipitation and fog drip, some information from University of Hawaii researchers puts the present agricultural water scenarios in perspective. Section 3.1 of this report summarizes important and relevant research of the University of Hawaii Economic Research Organization (UHERO) on the topic of estimating the costs and benefits of managing invasive species to protect and enhance watersheds.

1.3.5 Company and consultant reports

In addition to studies and reports by the University of Hawaii, the author referenced calculations in the 2010 Black and Veatch final report, *The Potential for Biofuels Production Hawaii* (Black & Veatch, 2010).

1.3.6 Various academic/journal literature

The following academic journal articles were useful references for providing input parameter values for estimating some biofuel crop yields and conversion to ethanol. The articles also provide calibrating metrics and calculations for checking the results of this present study:

- *Dryland Performance of Sweet Sorghum and Grain Crops for Biofuel in Nebraska* (Wortmann et al., 2010)
    - Provided methodology for estimating sugar content from sweet sorghum.
- *Evaluation of Sweet Sorghum for Fermentable Sugar Production Potential* (Smith et al., 1987)
    - Provided some early field trial data for growing sweet sorghum in Hawaii
- *Optimizing biofuel production: An economic analysis for selected biofuel feedstock production in Hawaii* (Tran et al., 2011)
    - Provides calibrating information for yields and costs of biofuels production in Hawaii

2. Scenarios Descriptions and Results

The water, food, and energy scenarios are based on the area of Central Maui as designated by the numbered land parcels in Figure 3. Each scenario assumes a single crop of plantation agriculture in the Central lowlands of Maui is irrigated from both surface water and groundwater as needed. The surface water comes from the East Maui Irrigation ditch system that diverts water from streams on the northeastern windward slopes of Maui (Cheng, 2012, Gingerich, 2005). Groundwater for irrigation comes from the existing groundwater pumps that service Hawaiian Commercial and Sugar (HC&S) agricultural lands (CWRM, 2010). For estimating the need for groundwater pumping, it is assumed that groundwater pumping only occurs for any given month if the crop evapotranspiration needs, including irrigation losses, exceed the water supplied by rainfall and surface irrigation water from the EMI system.

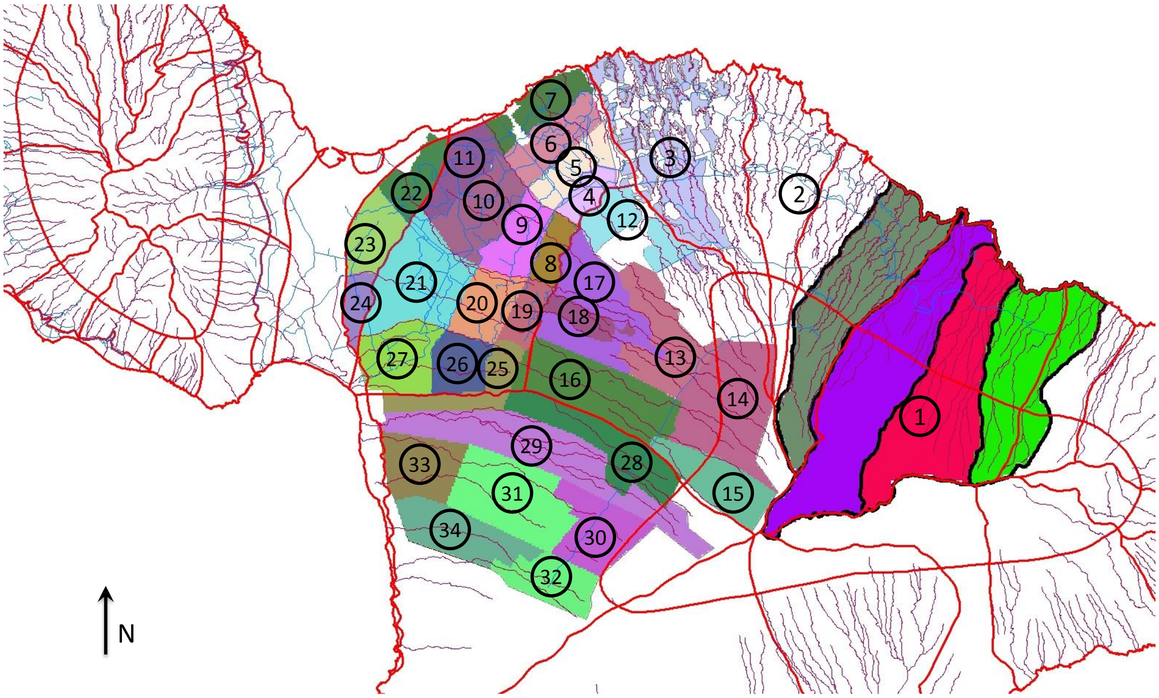

Figure 3. Central Maui is the focus of this study, and in particular the land parcels 4-24. The colored blocks represent individual land parcels of the model. Bold red lines delineate aquifers. Thin red lines emanating outward are streams. Light blue lines (running across streams) represent irrigation ditches.

2.1 Scenarios Descriptions

The water, food, and energy scenarios in this report are based upon the idea that Maui's water supplies are becoming increasingly constrained due to changes in climate, increasing native and visitor populations, and movements and legal rulings to reduce water diversions from streams for both environmental and native cultural reasons (e.g. taro farming). Further, many new water supplies such as more pipelines, groundwater wells, reclaimed water facilities, and desalination are constrained by the available capital required to invest in new fresh and potable water sources.

Worldwide, the agricultural sector consumes the most water compared to any other economic activity, and the water use on Maui Island is no different. On Maui, agriculture consumes > 90% of total water see Section 2.2.1.3). The current agricultural situation on East and Central Maui is that almost all of the surface water collected by major East Maui Irrigation (EMI) irrigation ditches is used for irrigating approximately 30,000 acres of sugar cane for HC&S (see descriptions of EMI ditch system in (Cheng, 2012) and (CWRM, 2010)). Further, the average water delivery from the EMI system is not enough to fulfill the full monthly water needs of the sugar cane to reach full yield, and groundwater is used for irrigation to supplement the surface water (see Exhibit G-1 of (CWRM, 2010)).

The scenarios presented in this report are structured to provide insight into the following questions about water, energy, and food on Maui:

- How does a smaller crop footprint (e.g. land use) for sugar cane relate to water use, groundwater sustainability, and yield?
- How much liquid biofuel can be produced from sugar cane in Central Maui?

- How do alternative biofuel crops compare in terms of water consumption?
- How much water and land is needed to grow a significant share of meat, dairy, fruits, and vegetables for Maui?
- How does a 'systems' combination of crops for biofuels and food relate to surface water use, groundwater sustainability, and broader sustainability goals for Hawaii and Maui?

This report does not present a full economic analysis of the costs, revenues, and profits for each scenario. The scenarios in this report are meant to serve as a basis for discussion on the topic of water use for food and energy on Maui. See (DWS, 2010) for detailed analysis of water supply options for Central Maui.

The scenarios begin with a "calibration" scenario that models the current 'water-deficit' situation as described by HC&S in Exhibit G-1 of (CWRM, 2010). Then, alternative scenarios are simulated on a smaller total crop footprint of 23,000 acres in Central Maui (eastern side) instead of the current 30,000 acres. As will be shown in the scenario results, growing sugar cane on 23,000 acres with full irrigation uses approximately the same quantity of water and to produce a similar total yield as 30,000 acres under water deficit.

Three alternative biofuel crops are modeled: sweet sorghum, cassava, and banagrass. Sugar cane, sweet sorghum, and cassava are modeled as 'conventional' biofuel crops for which there is a known commercial process for converting them to liquid biofuels, namely ethanol. The sugars produced from sugar cane and sweet sorghum can be fermented into ethanol, and the starch in cassava can be converted to sugars to produce ethanol in a similar manner as ethanol is produced from corn grain. Banagrass is a potential '2nd-generation' biofuel crop in that it does not produce sugars or starches, but instead its cellulose is converted to liquid fuels. Further, there is not yet a commercial process for converting the cellulosic material in banagrass into liquid fuels such as ethanol or synthetic hydrocarbons (e.g. jet fuel, diesel).

In the context of this report, a full comparison of banagrass to the other crops is not possible because of the lack of technology development for cellulosic biofuels[3]. Further, if cellulosic conversion to liquid fuels becomes commercial, then the significant cellulosic portions of sweet sorghum and sugar cane could also be converted to liquid fuels. The main reason that banagrass is included is that it has undergone a significant amount of research and testing in Hawaii, and research continues on both banagrass agriculture and biofuel conversion processes.

In addition to the biofuel scenarios, two food production scenarios are included. One food scenario is based on a concept of irrigated pasture for grass-fed cattle to produce both beef and milk (or other dairy products). In recent years, the cattle ranching on Maui has dwindled due to lack of rain for pasture grass, and the pasture scenario assumes the need for irrigating the grass. *Milk and beef production serve as proxy indicators* for output of consumer products from use of pasture land. There could be other scenarios for utilization of a relatively large acreage of ranch and pasture land on Maui. The other food scenario is for fruit and vegetable production, or "diversified agriculture". Thus, the food scenarios present one of many possible ways to utilize land on Maui for diary, protein, and fruit and vegetables. Future analyses could look at multiple scenarios to produce the same quantity of mass and nutrients (e.g. crops of nuts for protein instead of beef from cattle).

[3] Some valuable feedback upon presenting the scenarios to stakeholders was to avoid comparing banagrass-based (2nd generation) biofuels to those from 1st generation crops such as sugar cane, sweet sorghum, and cassava. For consistency and clarity, and due to the lack of full economic analysis, the report still often reports various scenario water and energy outputs together.

Table 1 summarizes the scenarios as follows:

Calibration – 30,000 acres sugar cane, water deficit: The calibration scenario assumes approximately 30,000 acres of sugar cane grown on current HC&S land using the average irrigation from Exhibit G-1 of (CWRM, 2010). Results are calculated for sugar and molasses production.

Scenario 1 – 30,000 acres sugar cane, full water: This scenario is the same as the calibration scenario, except groundwater pumping is increased to deliver the full water needs to the sugar cane crop. Results are calculated for ethanol production.

Scenario 2 – 23,000 acres sugar cane, full water: This scenario is a reduced footprint for sugar cane production to compare the water and yield to the calibration scenario and Scenario 1. Results are calculated for sugar and molasses production (Scenario 2s) and ethanol production (Scenario 2e).

Scenario 3 – 23,000 acres sweet sorghum, full water: This scenario is to compare sweet sorghum biofuel production and water needs to that of other biofuel crops.

Scenario 4 – 23,000 acres cassava, full water: This scenario is to compare cassava biofuel production and water needs to that of other biofuel crops. Two cassava yields are assumed: a 'standard' cassava yield (Scenario 4s) representative of existing commercial production, and an 'improved' cassava yield (Scenario 4i) based upon internal information to the Ulupono Initiative.

Scenario 5 – 23,000 acres banagrass, full water: This scenario is to compare anticipated banagrass biofuel production and water needs to that of other biofuel crops.

Scenario 6 – 5,850 acres pasture: This scenario models beef and milk production from grass-fed cattle in Upcountry Maui.

Scenario 7 – 1,000 acres diversified agriculture: This scenario models fruit and vegetable production in Upcountry Maui.

Scenarios 8 – System energy and food scenarios: These four 'system' scenarios combine the results for Scenarios 6 and 7 to each of the biofuel Scenarios 2e, 3, 4s, 4i, and 5.

Table 1. Land area of each land parcel, and description of which land parcels are modeled to have crops during each scenario. SC= sugar cane, SS = sweet sorghum, C = cassava, BG = banagrass, DA = diversified agriculture, and P = irrigated pasture grass.

		Scenarios								
	Parcel Area (acres)	Calibration	1	2s 2e	3	4s 4i	5	6	7	8*
Parcel 1	N/A	--	--	--	--	--	--	--	--	--
Parcel 2	N/A	--	--	--	--	--	--	--	--	--
Parcel 3	N/A	--	--	--	--	--	--	--	--	--
Parcel 4	1233	--	--	--	--	--	--	--	--	--
Parcel 5	2155	--	--	--	--	--	--	--	--	--
Parcel 6	2776	SC	SC	--	--	--	--	--	--	--
Parcel 7	2466	SC	SC	--	--	--	--	--	--	--
Parcel 8	1340	SC	SC	--	--	--	--	--	--	--
Parcel 9	2483	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 10	3712	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 11	2613	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 12	2788	--	--	--	--	--	--	--	--	--
Parcel 13	4457	--	--	--	--	--	--	--	--	--
Parcel 14	7079	--	--	--	--	--	--	--	--	--
Parcel 15	3466	--	--	--	--	--	--	--	--	--
Parcel 16	5853	--	--	--	--	--	--	P	--	P
Parcel 17	5135	--	--	--	--	--	--	--	--	--
Parcel 18	1000	--	--	--	--	--	--	--	DA	DA
Parcel 19	1519	SC	SC	--	--	--	--	--	--	--
Parcel 20	2545	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 21	5845	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 22	1941	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 23	2459	SC	SC	SC	SS	C	BG	--	--	Biofuel
Parcel 24	1227	--	--	SC	SS	C	BG	--	--	Biofuel
Parcel 25	2758	--	--	--	--	--	--	--	--	--
Parcel 26	2245	--	--	--	--	--	--	--	--	--
Parcel 27	3523	--	--	--	--	--	--	--	--	--
Parcel 28	4478	--	--	--	--	--	--	--	--	--
Parcel 29	8025	--	--	--	--	--	--	--	--	--
Parcel 30	3702	--	--	--	--	--	--	--	--	--
Parcel 31	5838	--	--	--	--	--	--	--	--	--
Parcel 32	2789	--	--	--	--	--	--	--	--	--
Parcel 33	3320	--	--	--	--	--	--	--	--	--
Parcel 34	3842	--	--	--	--	--	--	--	--	--

2.2 Scenarios Results: Average Monthly Surface Water Delivery

For detailed descriptions of all input values and assumptions, see the Appendix.

2.2.1 Water Balance

2.2.1.1 Calibration – 30,000 acres sugar cane, operated with water deficit

This calibration scenario serves to ensure that the model parameters and assumptions closely approximate the known data for water and energy flows on Maui. HC&S currently farms approximately 35,000 acres of land for sugar cane, but approximately 30,000 acres reside on the 'eastern' side of the Central valley of Maui. The modeling in this study only considers these 30,000 acres (see Figure 3 and Table 1). These calibration scenarios mimic the reported information that HC&S to the Hawaii Commission on Water Resources Management (CWRM, 2010). There are two main input data to compare the modeled results of the calibration scenarios to HC&S reported information: monthly surface water deliveries from EMI and monthly (capacity factor for) groundwater pumping. The calibration scenarios assume these two inputs as reported in Exhibit G-1 of (CWRM, 2010).

The calibration scenarios assumed the same pump capacity factors and surface water deliveries as reported by HC&S in (CWRM, 2010). Scenario 1 *and all subsequent scenarios* assume that irrigation is applied to fulfill full crop water need. Further, all subsequent scenarios assume slightly different surface water deliveries from East Maui Irrigation system ditches (see Table 2). All non-calibration scenarios use surface ditch inflows based upon stream gauge data for the Wailoa, Lowrie, New Hamakua, and Haiku ditches as collected by the USGS. See Appendix for description of stream gauge information.

Table 2. Surface water flows assumed for irrigation ditches in East Maui Irrigation system for the "calibration" and all other scenarios (units: million gallons per day). Sources: Exhibit G-1 of (CWRM, 2010) and USGS stream gauges.

	Calibration Scenarios, from Exhibit G-1 of (CWRM, 2010)	Scenarios 1-8
January	145	129
February	129	125
March	154	178
April	188	198
May	168	188
June	148	142
July	184	179
August	173	177
September	137	127
October	145	138
November	168	169
December	160	154

Here, two comparisons indicate the sensitivity of the model to an assumption regarding irrigation system losses, on HC&S land, due to seepage and evaporation in the storage reservoirs. Not considering the actual application of water to crops via drip irrigation, HC&S reported an estimated 10% of irrigation water is lost due to seepage and evaporation from their irrigation system, primarily due to multiple storage reservoirs (see description of Exhibit G-1 in (CWRM, 2010)). HC&S further notes that the seepage is expected to be higher when there is more water in the reservoirs, and this situation occurs during the wetter months of the winter and spring. Less seepage is expected in the drier months of the summer.

The model used for this report has separate factors for seepage (equivalent to groundwater recharge in the model) due to irrigation and evaporation of irrigation water. There is no separate factor for water seepage from the storage reservoirs. Two assumptions are compared: 3.3% of total irrigation water is evaporated (Figure 4) and 0% of total irrigation water is evaporated (Figure 5). Figure 4 (and summarizes the major water flows tracked in the model, and this structure is repeated throughout this section describing model results. The units are average daily flow in millions of gallons per day. Seven items are plotted in the left-hand graphic:

Irrigation: This black solid line indicates the monthly combined surface water and groundwater extraction used for irrigating crops.

Ditch Inflow: This gray solid line indicates the assumed surface water delivery form the EMI system.

HC&S Reported Groundwater Pumping: This is the quantity of groundwater pumping reported in Exhibit G-1 of (CWRM, 2010).

Modeled Groundwater Pumping: This is the modeled groundwater *extraction* for each scenario.

Recharge from Irrigation: This is the calculated quantity of water that seeps into the ground to recharge aquifers as a result of irrigation that is < 100% efficient.

Modeled Water Deficit: If this value is negative for any given month, there is a shortage of irrigation water relative to the full crop needs.

HC&S Reported Water Deficit: This is the reported average water deficit by HC&S in Exhibit G-1 of (CWRM, 2010).

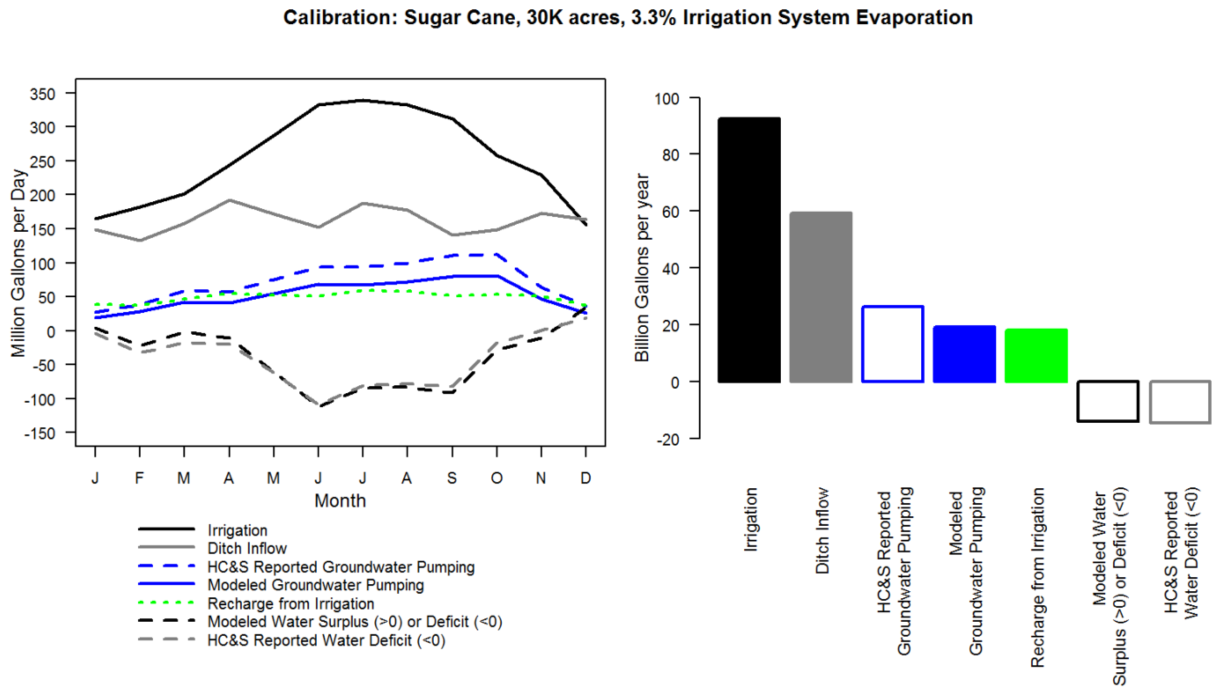

Figure 4. Monthly and annual water balances for the calibration scenario modeling 30,000 acres of sugar cane producing sugar. Here, the assumption is that 3.3% of irrigation water is lost to evaporation, and groundwater pumping occurs as reported by HC&S in Exhibit G-1 in (CWRM, 2010). A negative "Modeled Water Deficit" indicates not enough surface water and groundwater applied to crops

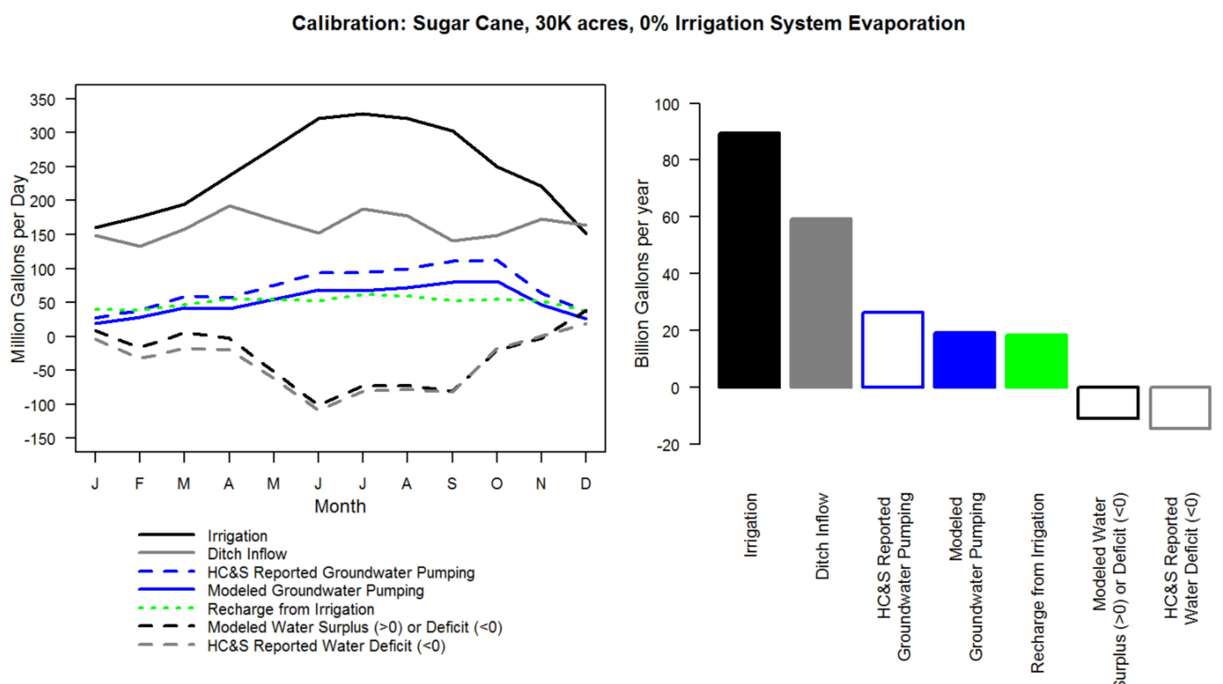

Figure 5. Monthly and annual water balances for the calibration scenario modeling 30,000 acres of sugar cane producing sugar. Here, the assumption is that 0% of irrigation water is lost to evaporation, and groundwater pumping occurs as reported by HC&S in Exhibit G-1 in (CWRM, 2010). A negative "Modeled Water Deficit" indicates not enough surface water and groundwater applied to crops.

The right-hand graphic of Figure 4 (and Figure 5 as well as subsequent similar figures for other scenarios) shows the same water flows as in the left-hand graphic but instead summed up for annual values.

There are a few important points to consider for the calibration scenario results. First, the model is in general agreement with results as reported in Exhibit G-1 of (CWRM, 2010). Given different assumptions for crop characteristics, irrigation practices and efficiency, and surface water deliveries, the water deficit could look significantly different. Nonetheless, there is a significant water deficit, particularly in the summer months (e.g. nearly 100 MGD deficit in an average June).

Second, both calibration scenarios closely follow the HC&S reported results. By accounting for some quantity of irrigation water evaporation (e.g. from storage reservoirs), the water deficit is larger, or more negative, for the 3.3% evaporation simulation (Figure 4) relative to the 0% evaporation simulation (Figure 5). For example, in June, there is a water deficit of 112 MGD versus 101 MGD for the 3.3% and 0% evaporation assumptions, respectively. Further, the modeled average annual water deficit is 14.2 billion gallons per year (BGY) and 11.2 BGY, respectively. Relative to the average values reported by HC&S, the 3.3% evaporation assumption slightly underestimates the crop water deficit (underestimates crop water needs) in the winter and spring and slightly overestimates the water deficit (overestimates crop water needs) in the fall.

The reported annual water deficit by HC&S at 14.7 BGY most closely matches the annual deficit using the 3.3% evaporation assumption. Thus, *all other* scenarios and results in this report assume that 3.3% of irrigation water is evaporated.

A third important point is that the calibration scenarios indicate that net groundwater extraction (= groundwater extraction – recharge from irrigation) is slightly positive, or very close to zero. Within the accuracy of the assumptions of this model, the net groundwater extraction can be considered zero. This point is important because it corroborates with the existing knowledge that current HC&S practices are not depleting the Maui aquifers over time. Net groundwater recharge could only occur because there is surface water delivered via the EMI system (i.e. you cannot only use water from an aquifer to irrigate crops and recharge more than has been extracted). In other words, it appears that the quantity of groundwater extracted at current practice is approximately equal to the aquifer recharge occurring due to irrigation of the sugar cane.

2.2.1.2 Explanation of Difference in Groundwater Pumping: This model vs. HC&S Reported

There is one significant difference between the modeled calibration scenarios and the reported HC&S results in Exhibit G-1 of (CWRM, 2010). The model calculates *less* groundwater *extraction* than reported groundwater *pumping* by HC&S. The explanation for this difference is that the model does not count "booster" pumping as water extraction. Instead, the model assumes that "booster" pumps only move groundwater that has already been extracted. Whereas HC&S reports 326 MGD of groundwater pumping capacity, this model uses a value of 242 MGD capacity, or 74% of the total pumping capacity reported in (CWRM, 2010). In other words, at 100% capacity, the model of this report assumes there could be 242 MGD of groundwater extraction, not 326 MGD.

Given the same input capacity factor for pumping and the model assumptions that assume HC&S booster pumps *do not* extract groundwater, the modeled groundwater extraction must be less than that reported as *pumping* by HC&S. It could be that HC&S intentionally did not report average groundwater extraction in Exhibit G-1 of (CWRM, 2010), and that their reported value is meant to include pumping for distributing water that has already been extracted (i.e. the table reports groundwater 'pumping' and perhaps not necessarily 'extraction'). The modeling does closely approximate the reported water deficit given the different assumption on pumping capacity, and this is a more important metric of consistency for calibration. See Appendix for full description of groundwater pumps and capacities.

2.2.1.3 Municipal Water Supply Comparison

How much water is used for irrigation, both surface water and groundwater, in comparison to the municipal water supply on Maui? Figure 6 shows the calibration scenario water consumption as compared to the total Maui municipal supply that includes both groundwater and surface water from both the Department of Water Supply and private providers (see Appendix for more details). Fifty percent of all DWS surface and groundwater supply is assumed to become sewage, meaning that 50% of municipal water is assumed consumed (e.g. evaporated, consumed in products, or infiltrated into groundwater). Thus, approximately 8 Bgal/yr of municipal supply is consumed. Assuming that all 92.4 Bgal/yr of sugar cane irrigation water is consumed, 92% of total modeled water consumption (92.4 / (92.4 + 8) = 0.92) is for agriculture (counting only sugar cane irrigation). Even though this ratio is higher than the U.S. and world average proportion of 70%-80% water consumption for irrigation, it is not necessarily an alarming result by itself (Solley et al., 1998). In most countries, irrigation dominates water *consumption* even though the agricultural sector usually accounts 40%-50% of total water *withdrawals*. The reason for this difference in proportion of water consumption and withdrawal is that the vast majority of irrigation water withdrawal is consumed whereas the vast majority of water withdrawal for industrial uses and power generation is returned to the environment (Kenny et al., 2009, King et al., 2013) (FAO: (http://www.fao.org/nr/water/aquastat/main/index.stm).

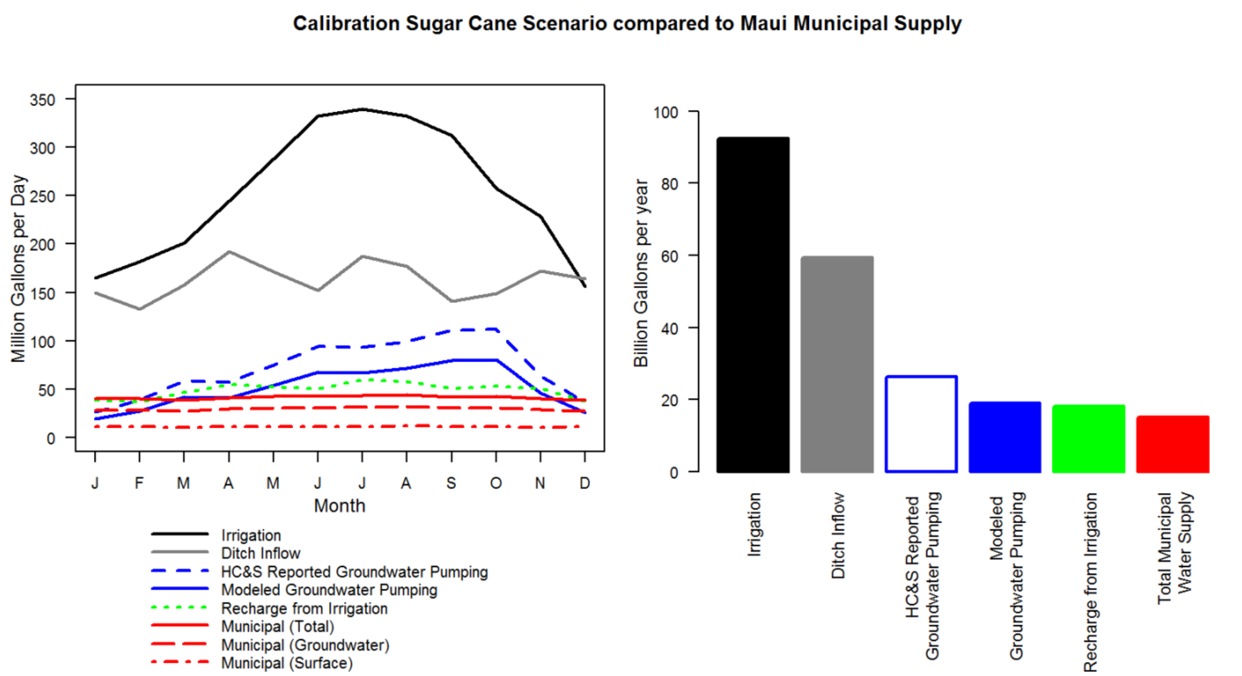

Figure 6. The total Maui municipal supply is approximately 15 Bgal/yr, primarily from groundwater, compared to 92 Bgal/yr in total irrigation for sugar cane.

2.2.1.4 Scenario 1 – 30,000 acres sugar cane, full water applied

The additional irrigation water for Scenario 1 comes from additional groundwater pumping (see Figure 7). The left-hand side of Figure 7 indicates no modeled water deficit for any month as this is part of the definition of the scenario. Further, modeled groundwater pumping, the same as extraction, is higher than aquifer recharge due to irrigation for all months except March, April, November, and December. The right-hand side of Figure 7 shows that the annual groundwater pumping (34.5 BGY) is significantly higher than the groundwater recharge from irrigation (21.9 BGY). The implication is that it is likely not possible to fully irrigate 30,000 acres of sugar cane while maintaining sustainable aquifer levels.

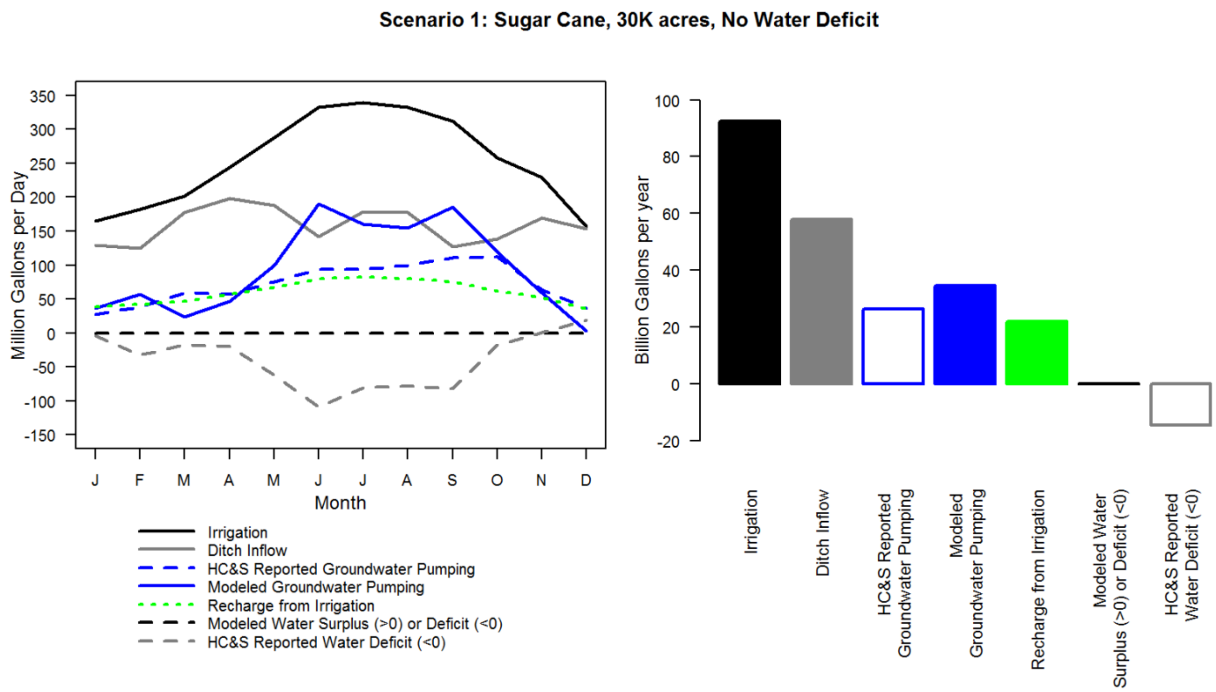

Figure 7. Monthly and annual water balances for the scenario modeling 30,000 acres of sugar cane producing sugar with groundwater pumping sufficient to meet full crop water needs. A positive "Modeled Water Deficit" indicates excess surface water.

2.2.1.5 Biofuel Scenarios 2, 3, 4 and 5

Given the results from Figure 4 – Figure 7, it seems unlikely to simultaneously fully irrigate 30,000 acres of sugar cane while maintaining a sustainable aquifer level. The biofuel scenarios presented in this section assume a smaller crop area of 23,000 acres that is fully irrigated. Figure 8 shows that 23,000 acres of sugar cane can be fully irrigated while having total groundwater pumping (extraction, 15 BGY) nearly equal to aquifer recharge from irrigation (16 BGY). The bulk of groundwater extraction for irrigation water occurs during the higher demand summer months. Monthly recharge from irrigation water is higher than groundwater extraction for all months except the summer and early fall. Because the crop evapotranspiration coefficient, Kc, is assumed equal for banagrass (12-month rotation) and sugar cane (24-month rotation), the groundwater extraction and recharge is the same for banagrass as for sugar cane (see Figure 11).

Scenario 2: Sugar Cane, 23K acres

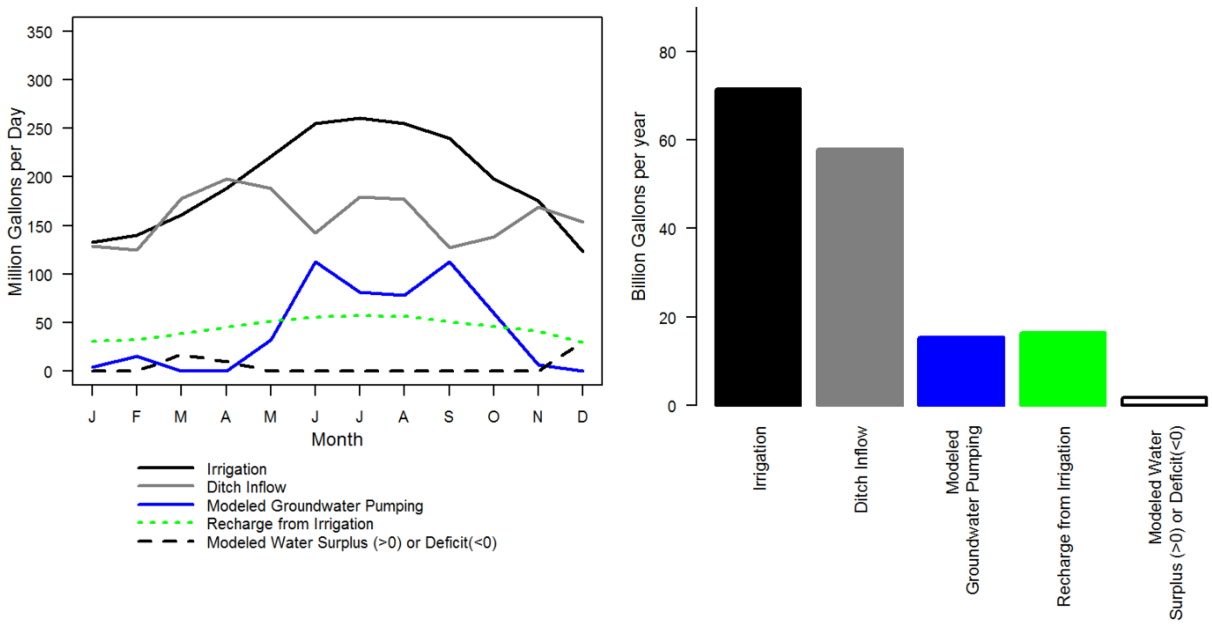

Figure 8. Monthly and annual water balances for the scenario modeling 23,000 acres of sugar cane, for ethanol, with groundwater pumping sufficient to meet full crop water needs. A positive "Modeled Water Deficit" indicates excess surface water.

Scenario 3: Sweet Sorghum, 23K acres

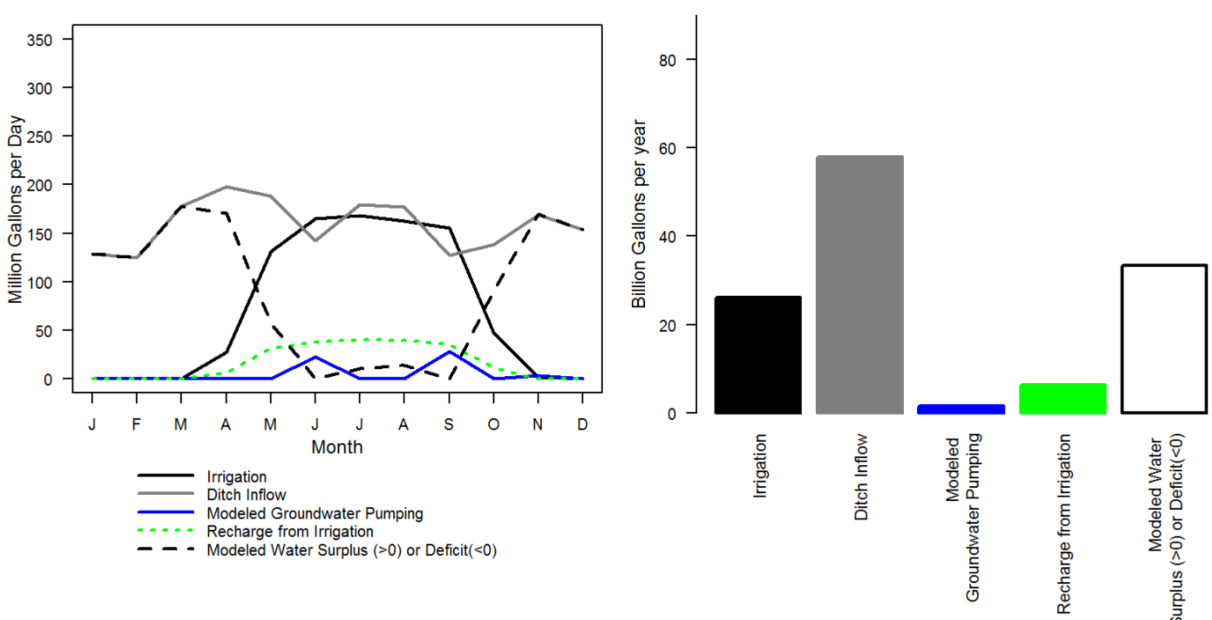

Figure 9. Monthly and annual water balances for the scenario modeling 23,000 acres of sweet sorghum, for ethanol, with groundwater pumping sufficient to meet full crop water needs. A positive "Modeled Water Deficit" indicates excess surface water.

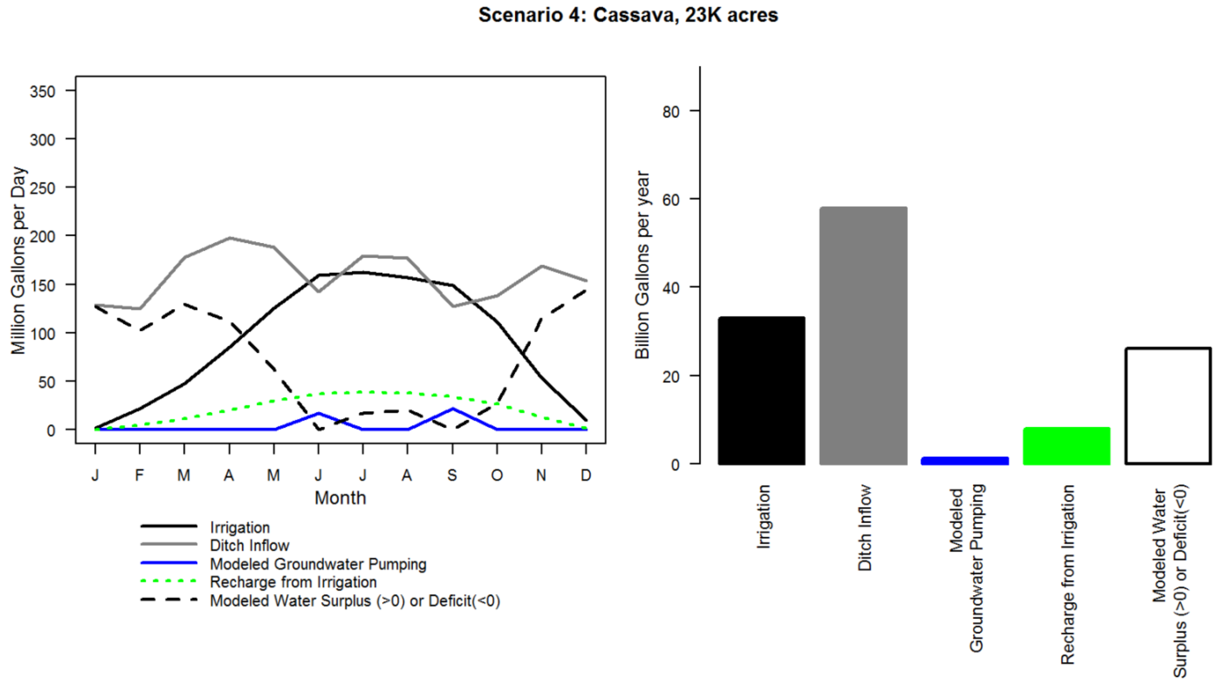

Figure 10. Monthly and annual water balances for the scenario modeling 23,000 acres of cassava, for ethanol, with groundwater pumping sufficient to meet full crop water needs. A positive "Modeled Water Deficit" indicates excess surface water.

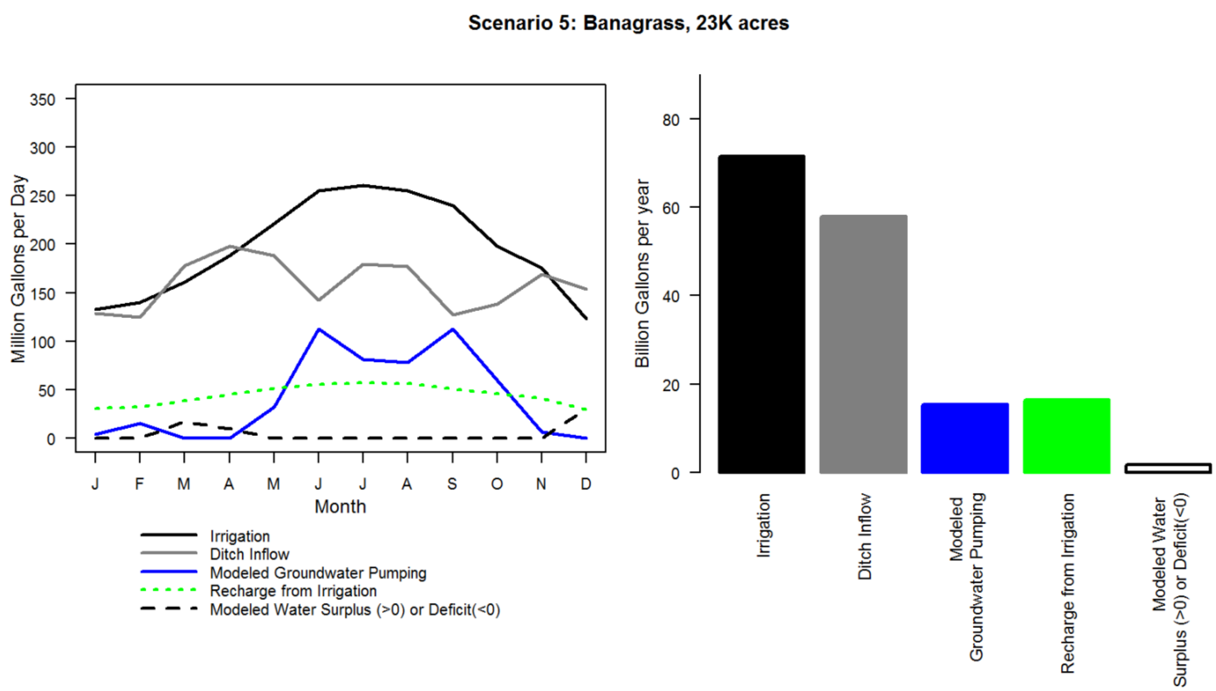

Figure 11. Monthly and annual water balances for the scenario modeling 23,000 acres of banagrass (same as sugar cane), for ethanol, with groundwater pumping sufficient to meet full crop water needs. A positive "Modeled Water Deficit" indicates excess surface water.

The calculated groundwater extraction for sweet sorghum is very low due to the model assumptions for a crop planting and relatively low yield for sweet sorghum from recent crop trials in Hawaii (see Figure 9 and Appendix for full description of assumptions). Each sweet sorghum harvest is assumed 3 months after the previous harvest. For any given land parcel, the model assumes sweet sorghum is planted in 3 monthly intervals such that the 1/3 of the total planted sorghum is harvested each month. Thus, the model assumes for any given land parcel that sweet sorghum is planted in February, March, and April to be harvested in April, May, June. The second harvest occurs in July, August, and September, and the third harvest occurs in October, November, and December. Because sweet sorghum does not appear to grow significantly in the spring, fall, and winter months due to less daylight as compared to the summer, the model assumes a large reduction in crop evapotranspiration. Lower growth and yield correspond to lower water uptake by the plant. For the context of Hawaii, more experimentation is needed to provide a full description of sweet sorghum yield to water needs.

Figure 10 shows the water balance for the modeled cassava crop. Since cassava is a root, the water needs are less than that of grasses. The modeled monthly crop evapotranspiration coefficient for cassava, on a 12-month rotation, is Kc = 0.66 compared to Kc = 1 as modeled for sugar cane. This difference in Kc explains the lower crop water needs for cassava that are similar to those assumed for sweet sorghum. For cassava irrigation, groundwater pumping is only needed in summer months that have relatively low surface water flows (e.g. average June and September). Just as with sweet sorghum, there is considerably more aquifer recharge from irrigation (7.9 BGY) than total groundwater extraction (1.2 BGY) because the vast majority of total irrigation (33 BGY) comes from surface water of EMI.

2.2.1.6 Food Scenarios 6 and 7

Scenario 6 models 5,580 acres of irrigated pasture grass[4] as a major part of the feed and nutrition for grass-fed cattle for beef and milk production. The crop evapotranspiration coefficient is assumed Kc=1 for all months, or the same as reference vegetative cover. As the pasture is assumed to reside in Upcountry Maui, with limited surface water access, the irrigation water is assumed to come from the Makawao aquifer at an electricity cost of 9,000 kWh per million gallons (see Appendix description of Section 1.2.1.2 "Electricity and capacity for groundwater pumping"). In the "stand alone" food scenarios, this assumption of the use of Makawao aquifer exists because there is presently no available and reliable surface water supply, at the needed flow quantities, to the Upcountry. Later, in the whole system scenarios including different biofuel feedstocks, more surface water is available due to lower biofuel crop water demand. Therefore, in the whole system scenarios that model cassava and sweet sorghum, it is possible that some surface water from the EMI ditch system could be pumped for pasture irrigation at a lower electricity intensity (~3,400 kWh per million gallons *lower* energy intensity) than groundwater pumping to high elevation. However, because of the timing of the pumping (during summer), there could be risks to Central Maui aquifer depletion to prevent high electricity consumption for pumping from the Makawao aquifer. See Section 2.2.2.7 for further discussion in the context of the energy and food system scenarios and costs.

The total irrigation need for the pasture grass (on Land Parcel 16 per Figure 3) is 5.4 BGY with net groundwater depletion per the assumption that no surface water is used for irrigation. The modeling estimates 1.7 BGY of recharge from irrigation for a net depletion of 3.6 BGY. However, there would be considerable recharge from rainfall as well. Assuming approximately 31 in/yr of rainfall (Giambelluca et al., 2013) and a recharge ratio of 0.45 (natural aquifer recharge / rainfall) from data in (Engott and Vana,

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[4] Per internal Ulupono Initiative information, the pasture grass is nominally assumed as kikuyu grass, or possibly a kikuyu and buffel grass mix, that is appropriate for supplying the bulk of fodder for the cattle diet, but not all nutritional needs.

2007) for the 5,850 acres of Land Parcel 16, there is approximately 2.2 BGY of natural recharge for current land use. Converting this current land use to pasture could increase or decrease recharge, and evapotranspiration, from the current vegetative cover. However, a more detailed study would be needed to determine if pasture grass for cattle, if irrigated from groundwater, would likely have a net depletion of groundwater. By maintaining grass in Upcountry Maui, there could be additional benefits in terms of maintaining soil quantity (e.g. erosion) and quality over time, and reducing the small amount of runoff that does occur.

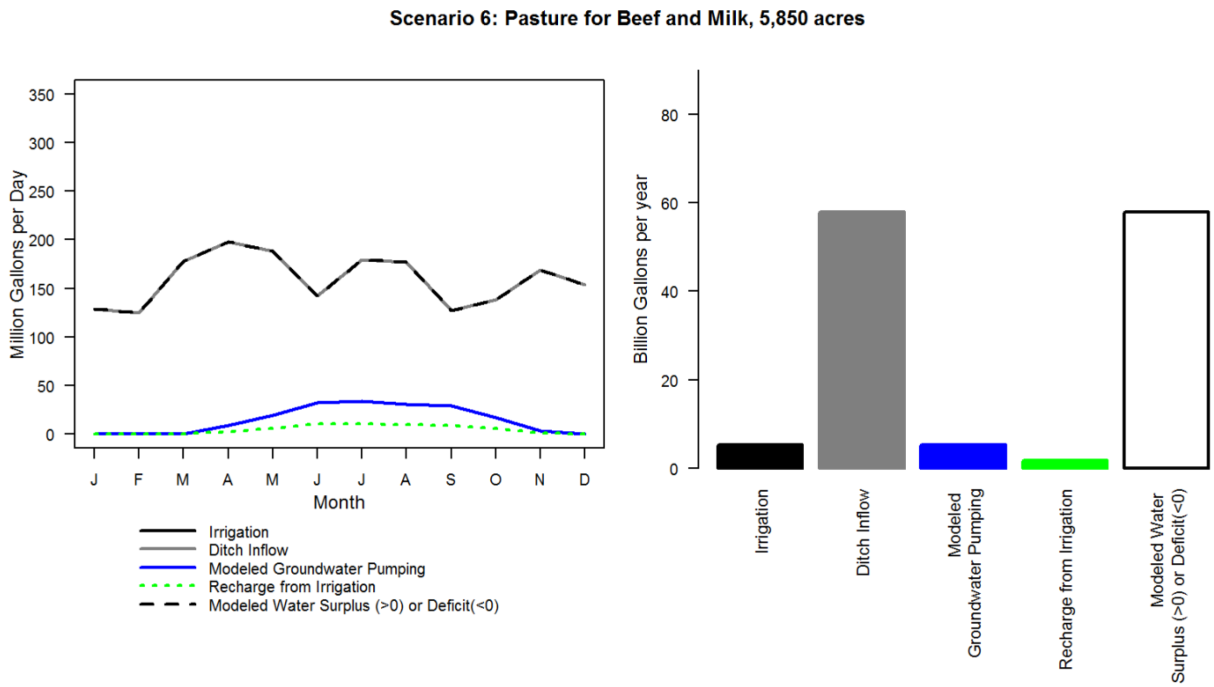


Figure 12. Monthly and annual water balances for the scenario modeling 5,850 acres of pasture grass (kikuyu grass) for grass-fed cattle for beef and milk production.

Scenario 7 models 1,000 acres of diversified agriculture in Upcountry Maui and shows relatively low irrigation needs based upon the assumed crops (bananas, dry onions, lettuce, and cabbage) and planting/harvest schedule (see Appendix). Only 0.5 BGY of irrigation are required (all assumed from diverted surface water with no pumping needs).

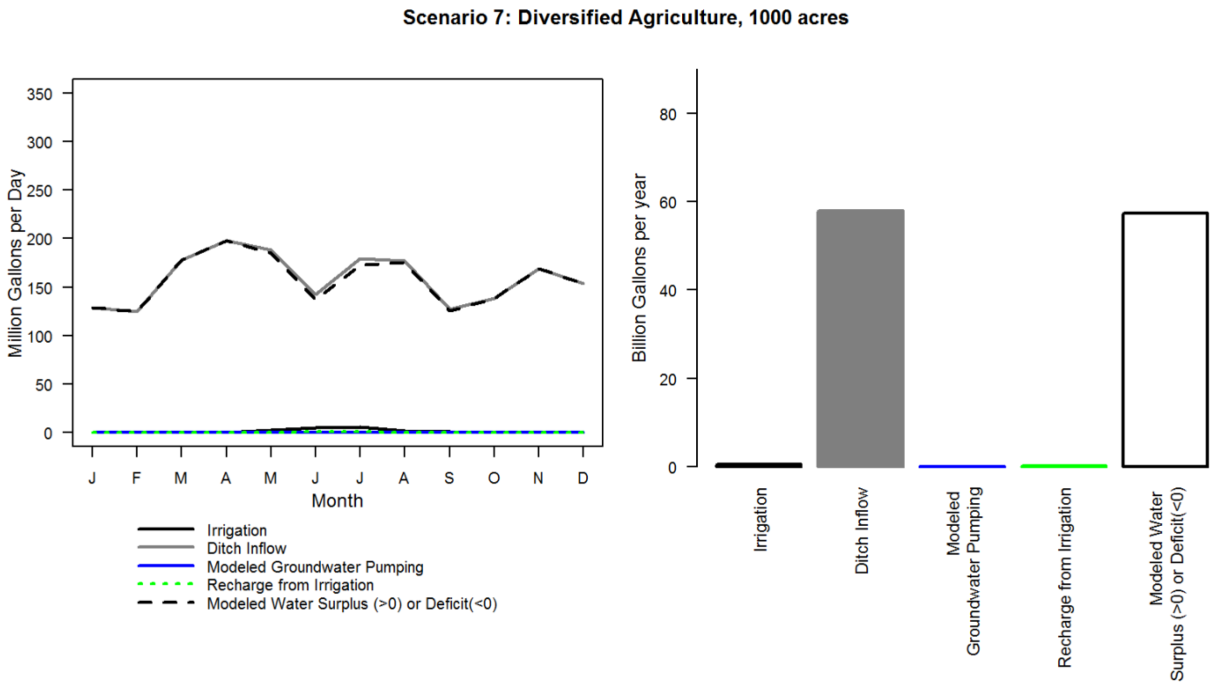


Figure 13. Monthly and annual water balances for the scenario modeling 1,000 acres of diversified agriculture (fruits and vegetables), with irrigation assumed from surface water (e.g. from Kula ditch or pumped from EMI system).

2.2.1.7 System Energy and Food Scenarios

Figure 14 and Figure 15 show the monthly and annual water balances, respectively, for the four 'system' scenarios that combine the biofuel crops with the food crops (grass for cattle and diversified agriculture). As with the previous results for each specific scenario, the aquifer recharge data plotted in Figure 14 and Figure 15 do not include any natural recharge from land parcels that are not modeled to have a planted crop. Further, no recharge from precipitation is modeled if that were to occur either during fallow periods or during the crop growth cycle.

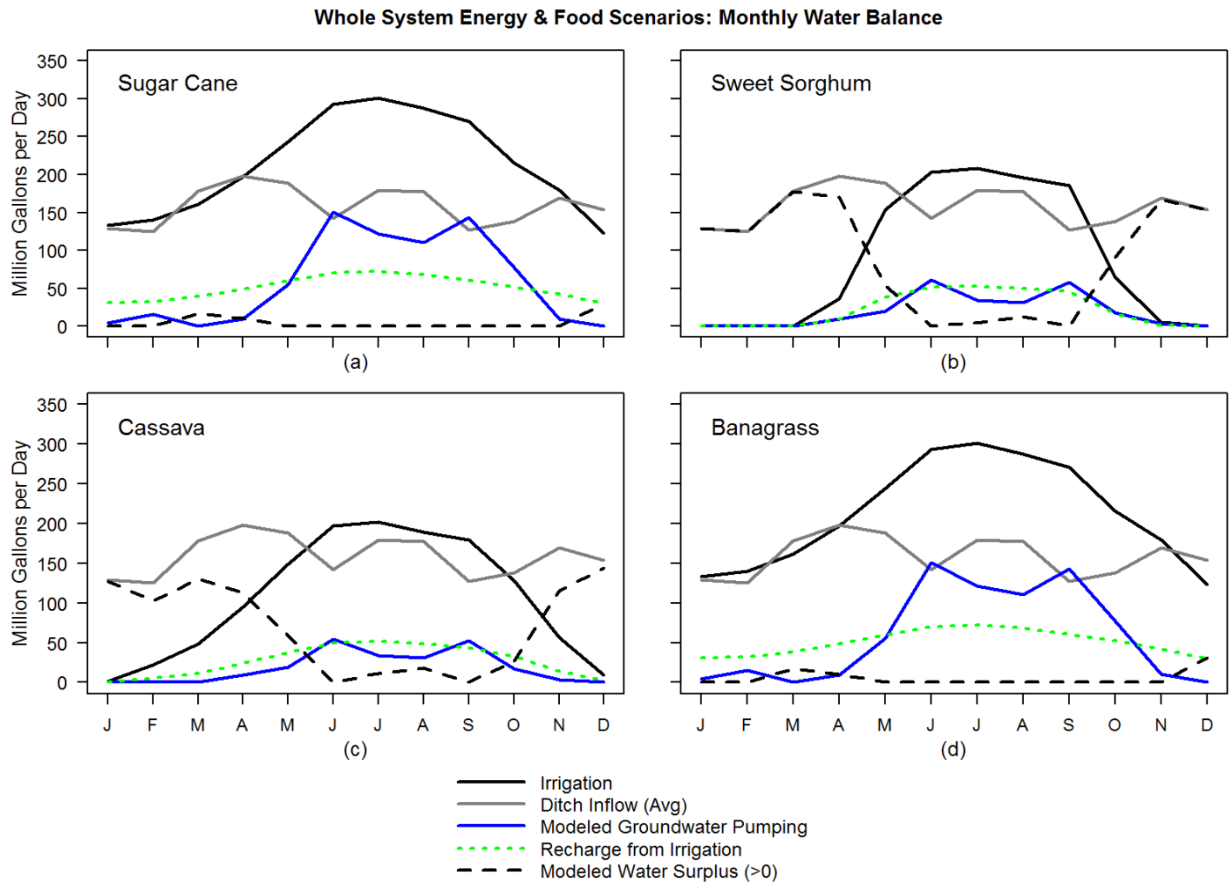


Figure 14. The *monthly* water balances, assuming monthly average EMI ditch inflows, for the four 'system' energy and food scenarios using biofuel feedstocks of (a) sugar cane (Scenario 2e), (b) sweet sorghum (Scenario 3), (c) cassava (Scenarios 4s and 4i), and (d) banagrass (Scenario 5).

The figures show that the majority of groundwater pumping occurs during the summer months and that the overall net groundwater balance (= groundwater extraction – groundwater recharge from irrigation) is close to zero for all scenarios, but with the sugar cane and banagrass scenarios tending toward net extraction of groundwater while the cassava and sweet sorghum scenarios tend toward net recharge of groundwater while extracting significantly less groundwater.

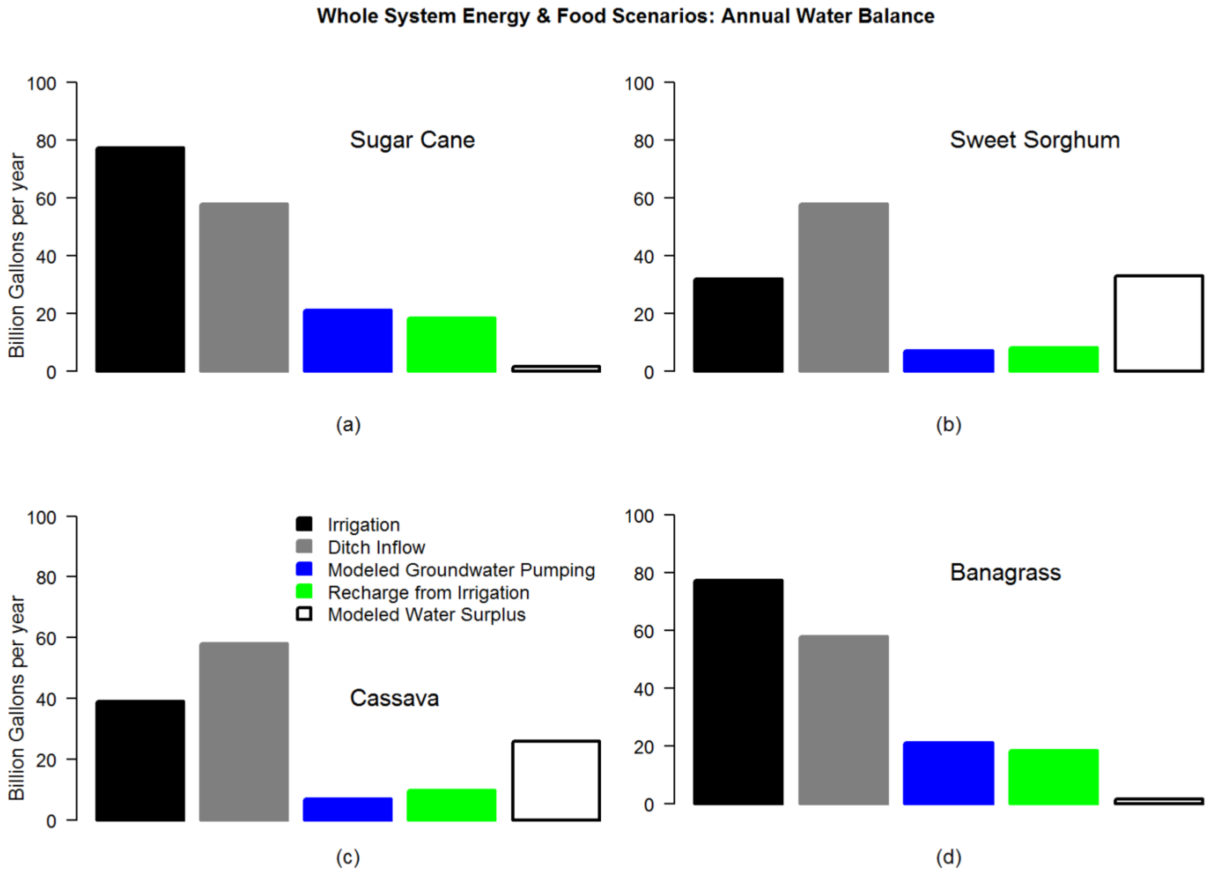


Figure 15. The *annual* water balances for the four 'system' energy and food scenarios using biofuel feedstocks of (a) sugar cane (Scenario 2e), (b) sweet sorghum (Scenario 3), (c) cassava (Scenarios 4s and 4i), and (d) banagrass (Scenario 5). A positive "modeled water deficit" means that there is excess surface water over the course of the year due to certain months having ditch inflows > irrigation needs.

2.2.1.8 Water Balance: Scenarios Summary

A comparative look at net groundwater recharge, due to irrigation needs, is useful for understanding qualitative differences in groundwater sustainability for each of the modeled scenarios. For each scenario, Figure 16 plots total groundwater extraction, total groundwater recharge from irrigation water (only), and the net groundwater extraction. Here, if net groundwater extraction is negative, then there is groundwater depletion, and if net groundwater extraction is positive, there is groundwater recharge over the course of the year. Figure 16 shows the same data as previously displayed in this Section 2.2.1, but in a more compact form focused on groundwater.

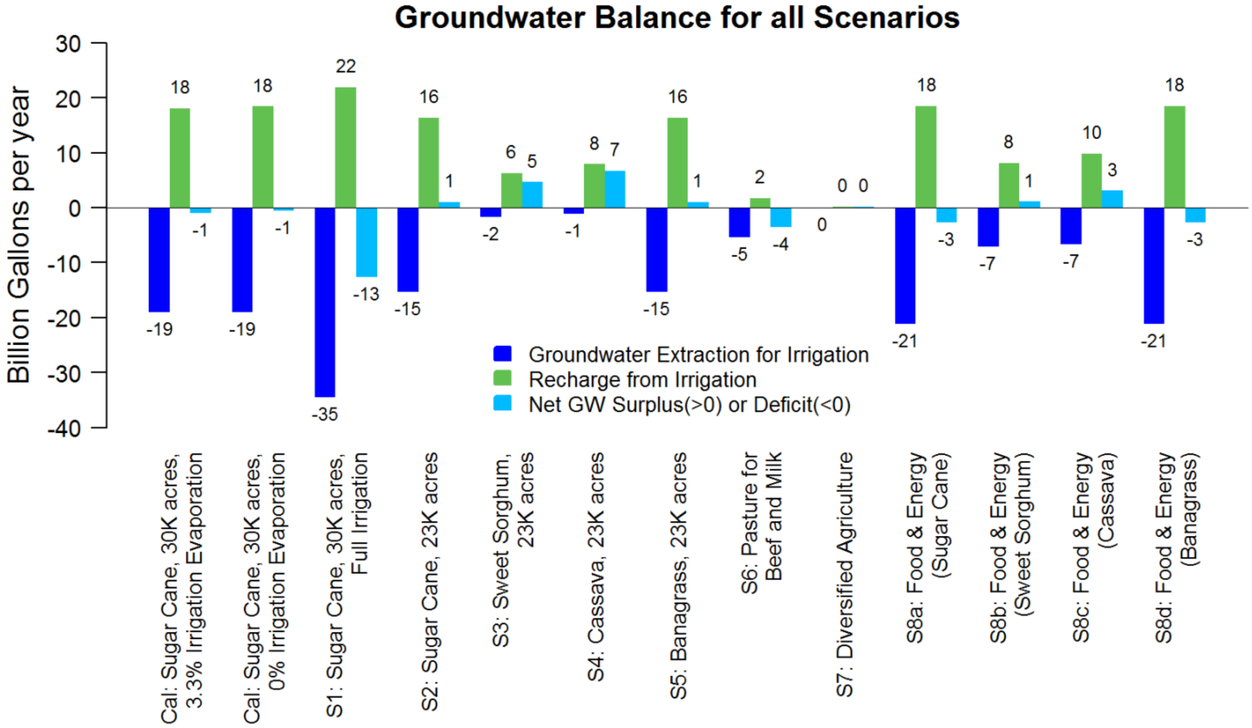


Figure 16. The groundwater extraction, recharge from irrigation, and net groundwater extraction provide summary metrics to compare the groundwater sustainability of all scenarios (average monthly rain and EMI ditch flows).

The major takeaways from Figure 16 are:

- Current irrigation practice for 30,000 acres of sugar cane causes approximately zero net groundwater extraction (for an average year).
- Fully irrigating 30,000 acres of sugar cane is likely unsustainable for the Maui aquifers.
- Fully irrigating 23,000 acres of sugar cane causes approximately zero net groundwater extraction (for an average year).
- Fully irrigating 23,000 acres of sweet sorghum (because of low yield and evapotranspiration assumptions) or cassava needs very little groundwater for irrigation causing a net groundwater recharge if surface water is first used (before groundwater) as needed and available.
- Largely driven by the assumption of irrigation using *only* groundwater from the Makawao aquifer for the pasture scenario, the "Food & Energy" scenarios are slightly positive (sorghum and cassava) to slightly negative (sugar cane and banagrass) in terms of total net groundwater extraction. More detailed investigation should refine each scenario and assess the viability of other water supplies for Upcountry pasture. The 23,000 acres of biofuel crops and 5,850 acres for pasture affect different aquifers. The biofuel crops overlie the Paia and Kahului aquifers, and the modeled pasture land overlies the Makawao aquifer.

The main aquifers of interest for this study are the Paia and Kahului with sustainable yield confidence ranking of 2 (intermediate), and the Makawao aquifer with a confidence ranking of 3 (low)[5]. From Figure

[5] The confidence ranking of aquifer sustainable yields is taken from Table 3-11 of Wilson Okamoto Corporation (2008) Hawaii 2008 Water Resource Protection Plan Update. Department of Land and Natural Resources. where the

16 one can see that only Scenario 1 assuming full irrigation of 30,000 acres of sugar cane has a significant net reduction in groundwater recharge from irrigation water. The sustainable aquifer yield for the Central Maui area aquifers overlying the 23,000 acres of biofuel feedstocks is only 8 MGD, or 3 BGY (1 MGD for Kahului aquifer, 7 MGD for the Paia aquifer, (Wilson Okamoto Corporation, 2008)). These yields are based on the basal[6] groundwater estimates and not related to agricultural land use and irrigation practices. With the exception of Scenario 1 with full irrigation to 30,000 acres of sugar cane, all scenarios use groundwater at a sustainable rate. These scenarios have a net groundwater extraction that is greater than -8 MGD (or > -3 BGY as in Figure 16). In other words, if any land use scenario extracts *8 MGD (3 BGY) or more* (over the Kahului and Paia aquifers) than it recharges from irrigation, then that the groundwater use is likely not sustainable.

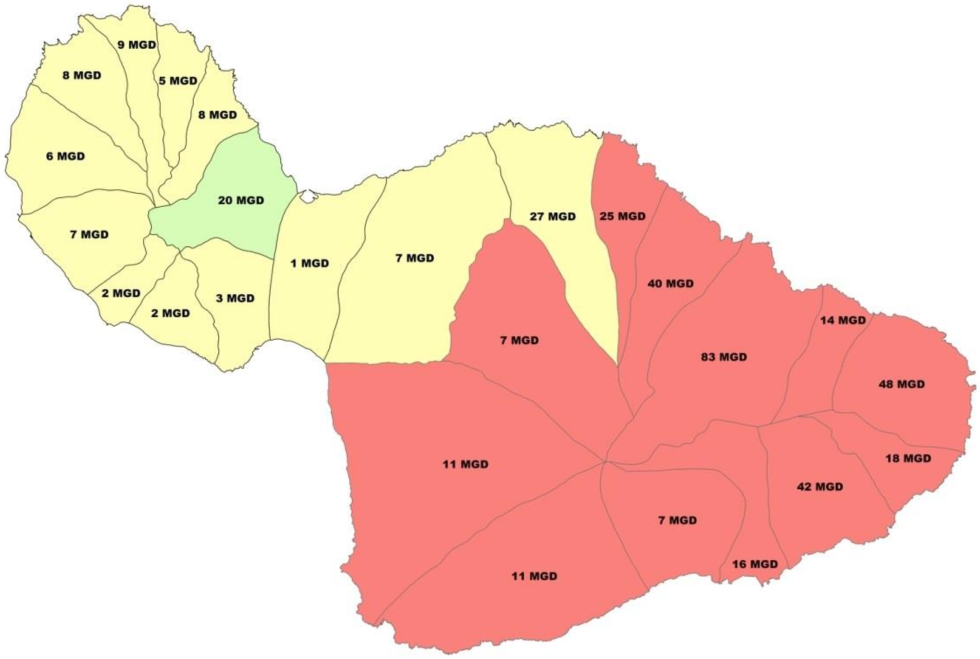


Figure 17. The estimated sustainable yields for Maui aquifers (data from (Wilson Okamoto Corporation, 2008)). The green shade indicates the yield estimate has a "most confident" ranking (=1), yellow a "moderately confident" ranking (=2), and red a "least confident" ranking (=3).

2.2.2 Energy and Food Outputs

To facilitate the discussion of scenarios and relevance to sustainability, the energy and food outputs are reported in both *absolute* quantities (e.g. tonnes of sugar, gallons of ethanol) and quantities *relative* to estimated consumption on Maui (e.g. percentage of gasoline demand that can be supplied by ethanol). All scenarios use ethanol as the biofuel product, but this ethanol assumption acts only as a proxy for ease of comparison, not necessarily as a commercial recommendation. Table 3 lists the baseline Maui-specific values of food consumption and production, gasoline consumption, and gross electricity production to which the energy and food scenarios are compared. Table 3 values represent an approximate "current" year (data from 2009 to 2012) situation for energy and food consumption and production (on Maui).

The scenario outputs for energy and food production are shown in Table 4 and Table 5, respectively. For consistency, the tables report values for each piece of information for each scenario even if that

rankings relate to the quantity of hydrologic data available: 1 (most confident) = significant hydrologic data, 2 (moderately confident) = moderate hydrologic data, and 3 (least confident) = limited to no hydrologic data.

[6] Basal groundwater is that groundwater that floats on and is in hydrodynamic equilibrium with sea water.

scenario is not meant to indicate a change from the baseline in Table 3. This Subsection 2.2.2 first discusses the electricity needs for the municipal supply to compare to electricity needs for irrigation groundwater extraction. Then, subsequent subsections discuss the energy and food outputs for each scenario.

2.2.2.1 Municipal Supply Electricity Consumption Compared to Calibration Scenario

Table 4 includes the electricity needs for groundwater pumping for crop irrigation as well as electricity consumption for the Maui's municipal supply of water and wastewater treatment. Recall Figure 6 indicating an annual municipal supply of 15 Bgal/yr. This municipal supply requires approximately 59 GWh/yr for groundwater pumping, water distribution, and wastewater treatment (see Appendix for more details). The municipal supply needs approximately 32 GWh/yr for groundwater pumping alone. Adding the estimated 20 GWh/yr required for pumping water for the sugar cane calibration scenario, and the calibration scenario estimates 6% of Maui gross electricity generation is used for water extraction, pumping, and treatment.

2.2.2.2 Calibration – 30,000 acres sugar cane, operated with water deficit

The modeled sugar and molasses production for the calibration scenario is 155,000 (170,000) and 51,000 (56,000) metric tonnes (short tons), respectively. These quantities compare well with reported HC&S sugar production for 2010 (Alexander & Baldwin, 2011). See Appendix for more detail on estimation of yield of sugar cane, sugar, and molasses. The gross biomass electricity production of 88 GWh/yr, with net 35 GWh/yr of biomass electricity, represents current practice of HC&S that by contract sends approximately 40% of its biomass power to the Maui Electric Company grid such that greater than 50% of electricity sent to the grid by HC&S is renewable. The 88 GWh/yr of biomass electricity is representative of reported data by HC&S and to the Energy Information Administration (Alexander & Baldwin, 2011, EIA, 2009). Importantly, the HC&S Puunene sugar mill also burns coal to power the facility and sugar refining processes. In this sense, the quantity of exported coal versus biomass electricity is somewhat arbitrary, and the current biomass power is not sufficient to fully operate the Puunene mill.

Table 3. Baseline Maui resident consumption of food and energy for comparison to production system energy and food scenarios.

	Estimated Consumption on Maui	Estimated Production on Maui	Units	Percent Local Production on Maui	Source
Total gross electricity generation	1,364	- -	GWh/yr	26%	a
Wind electricity	242	242	GWh/yr	100%	b
Hydropower	18	18	GWh/yr	100%	a
Biomass generation	91	91	GWh/yr	100%	a
Gasoline	1,265	0	MMBBL/yr	0	c
Gasoline	6.6	0	TBtu/yr	0	c
Milk	3,718,000	0	gallons/yr	0	d, e
Beef	4,600	37	short tons/yr	37	d, e
Fruits and Vegetables	22,400	3,600	tonnes/yr	3,600	d, e

a: EIA-923, 2009.

b: Wind power is Kaheawa I (30 MW) and Auwahi wind (21) MW at 45% capacity factor, and Kaheawa II (21 MW) at 22.5 % capacity factor.

PUC (2013) http://www.mauielectric.com/vcmcontent/IntegratedResource/IRP/PDF/IRP-2013-Report-Chapter-18.pdf. DBEDT (2013), Hawaii Energy Facts and Figures, June 2013: http://energy.hawaii.gov/wp-content/uploads/2011/10/FF_June2013_R2.pdf). PUC (2013) reports 238 GWh/yr of total renewables in MECO. DEBDT (2013) reports (in graphical format) approximately 150-170 GWh of wind in MECO (all on Maui island) in 2012, and a capacity factor of 47% for Auwahi wind farm. DEBDT also reports a 45% capacity factor assumption for estimates on Maui. PUC (2013) also reports the PPA for Kaheawa II wind farm is for < 50% of anticipated generation. Maui wind power in 2009 was 110 GWh/yr as reported in (EIA-923, 2009). No specific wind power for Maui was reported to EIA for 2010 or 2011.

c: Assuming 11.128 million barrels of gasoline (MMBBL/yr) consumed in Hawaii, with 11.4% of Hawaii 2010 population on Maui (158,226 on Maui) consuming gasoline at an average rate. Gasoline data from EIA: http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_fuel/html/fuel_mg.html&sid=HI. Population data from "Cumulative Estimates of Resident Population Change and Rankings: April 1, 2010 to July 1, 2012; U.S. Census Bureau, Population Division"

d: Maui Consumption: Per capita consumption fruit and vegetables in Hawaii of 321.3 lb/person/yr multiplied by Maui 2010 population. Per capita consumption milk and cream in Hawaii of 23.5 lb/person/yr multiplied by Maui 2010 population. Per capita consumption beef in Hawaii of 58.2 lb/person/yr multiplied by Maui 2010 population. Food data from ERS, USDA; 2009; Table 218. Per Capita Utilization of Selected Commercially Produced Fruits and Vegetables: 1980 to 2009.

e: Maui Production: Production of 9,420,000 lbs of fruits and vegetables from "Maui County Data Book 2011" (includes the following crops produced on Maui: beans, cabbbage, cucumbers, onions, romaine, squash, taro and bananas). Maui Diversified Agriculture baseline production is reduced by 16% to account for loss of food from producer to consumer (source: "Wasted -How America is Losing up to 40% of its food from Farm to Fork to Landfill." Food and Agriculture Organization 2011). Baseline beef production assumes Maui Cattle Company is only beef producer at recent (2011-2013) annual production of 120 head/yr at 621 lb/head for 74,500 lb/yr = 37 metric tonnes/yr of beef.

Table 4. Scenario energy inputs (electricity, *net electricity is 0%–40% of gross electricity) and outputs (electricity and ethanol).

	Scenario	**Cal**	**Cal**	**1**	**2s**	**2e**	**3**	**4s**	**4i**	**5**
		Sugar Cane, 30K acres, 3.3% evap.	**Sugar Cane, 30K acres, 0% evap.**	**Sugar Cane, 30K acres, full water**	**Sugar Cane 23K acres, sugar**	**Sugar Cane, 23K acres, EtOH**	**Sweet Sorghum, 23K acres, EtOH**	**Cassava "standard" yield, 23K acres, EtOH**	**Cassava "improved" yield, 23K acres, EtOH**	**Banagrass, 23K acres, EtOH**
Energy Self-sufficiency: Electricity	**% Renewable gross electricity**	26%	26%	27%	25%	25%	28%	22%	24%	26%
	Gross Generation (from crop biomass) (GWh/yr)	88	88	111	86	86	120	41	62	95
	Net Generation (from crop biomass) (GWh/yr)*	35	35	44	0–34	0–34	0–48	0–3.6	0–5.4	0–38
	Non-biomass Renewable Generation (GWh/yr)	260	260	260	260	260	260	260	260	260
Electricity for Groundwater Pumping	**% of Maui gross generation for pumping**	6%	6%	7%	5%	5%	4%	4%	4%	5%
	Electricity for pumping groundwater to crops (GWh/yr)	20	20	32	12	12	1.8	0.7	0.7	12
	Electricity for DWS, TOTAL (GWh/yr)	59	59	59	59	59	59	59	59	59
	Electricity for DWS, groundwater pumping ONLY (GWh/yr)	32	32	32	32	32	32	32	32	32
Energy Self-sufficiency: Liquid Transport Fuels	**% Gasoline energy supplied by EtOH (Btu EtOH/Btu gasoline)**	0%	0%	0%	0%	31%	12%	26%	40%	43%
	Ethanol Produced (Million Gallons/yr)	NA	NA	NA	NA	27.1	10.1	22.9	34.3	37.4
	Ethanol Produced (Trillion Btu/yr)	NA	NA	NA	NA	2.1	0.8	1.7	2.6	2.8
	Gallons EtOH/acre	NA	NA	NA	NA	1,200	440	1,000	1,500	1,640

Table 4. Scenario energy inputs (electricity, *net electricity is 0%–40% of gross electricity) and outputs (electricity and ethanol). (continued)

	Scenario	**6**	**7**	**8a**	**8b**	**8c,s**	**8c,i**	**8d**
		Pasture Beef and Dairy	**Diversified Agriculture**	**Energy & Food: Sugar Cane**	**Energy & Food: Sweet Sorghum**	**Energy & Food: Cassava "standard"**	**Energy & Food: Cassava "improved"**	**Energy & Food: Banagrass**
Energy Self-sufficiency: Electricity	**% Renewable gross electricity**	19%	19%	25%	28%	22%	24%	26%
	Gross Generation (from crop biomass) (GWh/yr)	0	0	87	120	41.4	62.1	95
	Net Generation (from crop biomass) (GWh/yr)*	0	0	0–35	0–48	0–3.6	0–5.4	0–38
	Non-biomass Renewable Generation (GWh/yr)	260	260	260	260	260	260	260
Electricity for Groundwater Pumping	**% of Maui gross generation for pumping**	8%	4%	9%	8%	8%	8%	9%
	Electricity for pumping groundwater to crops (GWh/yr)	51	0	64	52	52	52	64
	Electricity for DWS, TOTAL (GWh/yr)	59	59	59	59	59	59	59
	Electricity for DWS, groundwater pumping ONLY (GWh/yr)	32	32	32	32	32	32	32
Energy Self-sufficiency: Liquid Transport Fuels	**% Gasoline energy supplied by EtOH (Btu EtOH/Btu gasoline)**	0%	0%	32%	12%	26%	40%	43%
	Ethanol Produced (Million Gallons/yr)	NA	NA	27.5	10.1	22.9	34.3	37.4
	Ethanol Produced (Trillion Btu/yr)	NA	NA	2.1	0.8	1.7	2.6	2.8
	Gallons EtOH/acre	NA	NA	1,200	440	1,000	1,500	1,640

Table 5. Scenario food outputs (diversified agriculture, milk, and beef) including sugar for calibration scenarios. EtOH = ethanol.

	Scenario	Cal	Cal	1	2s	2e	3	4s	4i	5
		Sugar Cane, 30K acres, 3.3% evap.	Sugar Cane, 30K acres, 0% evap.	Sugar Cane, 30K acres, full water	Sugar Cane 23K acres, sugar	Sugar Cane, 23K acres, EtOH	Sweet Sorghum, 23K acres, EtOH	Cassava “standard" yield, 23K acres, EtOH	Cassava "improved" yield, 23K acres, EtOH	Banagrass, 23K acres, EtOH
Self-Sufficiency: Food Production	**Diversified Ag.: Production as % of consumption**	16%	16%	16%	16%	16%	16%	16%	16%	16%
	Scenario production (tonnes)	0	0	0	0	0	0	0	0	0
	Total Local production (tonnes)	3,589	3,589	3,589	3,589	3,589	3,589	3,589	3,589	3,589
	Milk: Production as % of consumption	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Scenario production (gallons)	0	0	0	0	0	0	0	0	0
	Total Local production (gallons)	0	0	0	0	0	0	0	0	0
	Beef: Production as % of consumption	1%	1%	1%	1%	1%	1%	1%	1%	1%
	Scenario production (short tons)	0	0	0	0	0	0	0	0	0
	Total Local production (short tons)	37	37	37	37	37	37	37	37	37
	Sugar production (tonnes)	155,000	155,000	195,000	150,000	0	0	0	0	0
	Molasses production (tonnes)	51,000	51,000	64,000	50,000	0	0	0	0	0

Table 5. Scenario food outputs (diversified agriculture, milk, and beef) including sugar for calibration scenarios. (continued)

	Scenario	6	7	8a	8b	8c,s	8c,i	8d
		Pasture Beef and Dairy	**Diversified Agriculture**	**Energy & Food: Sugar Cane**	**Energy & Food: Sweet Sorghum**	**Energy & Food: Cassava "standard"**	**Energy & Food: Cassava "improved"**	**Energy & Food: Banagrass**
Self-Sufficiency: Food Production	**Diversified Ag.: Production as % of consumption**	16%	69%	69%	69%	69%	69%	69%
	Scenario production (tonnes)	0	14,205	14,205	14,205	14,205	14,205	14,205
	Total Local production (tonnes)	3,589	15,521	15,521	15,521	15,521	15,521	15,521
	Milk: Production as % of consumption	100%	0%	100%	100%	100%	100%	100%
	Scenario production (gallons)	3,717,000	0	3,717,000	3,717,000	3,717,000	3,717,000	3,717,000
	Total Local production (gallons)	3,717,000	0	3,717,000	3,717,000	3,717,000	3,717,000	3,717,000
	Beef: Production as % of consumption	40%	1%	41%	41%	41%	41%	41%
	Scenario production (short tons)	1,852	0	1,852	1,852	1,852	1,852	1,852
	Total Local production (short tons)	1,889	37	1,889	1,889	1,889	1,889	1,889
	Sugar production (tonnes)	0	0	0	0	0	0	0
	Molasses production (tonnes)	0	0	0	0	0	0	0

2.2.2.3 Scenario 1 – 30,000 acres sugar cane, full water applied

The modeled sugar and molasses production when assuming the 30,000 acres of sugar cane is fully irrigated produces more output than under the assumption of a water deficit. As discussed in the Appendix and using data supplied by HC&S in (CWRM, 2010), this model approximates sugar cane as a function of the percentage of water provided to the crop relative to total crop water needs. Applying enough irrigation water to reach full sugar cane yield produces approximately 195,000 (215,000) and 64,000 (71,000) metric tonnes (short tons) of sugar and molasses, respectively. These quantities are meant to match, and compare well with, reported HC&S sugar production when receiving enough water to provide for 100% of crop need. In Exhibit G-1 of (CWRM, 2010), HC&S notes a yield of 14.7 tons of sugar per acre when harvesting a 2-yr sugar cane crop with water availability greater than 100% crop needs. The present model estimates 215,000 tons/15,000 acres = 14.4 tons/acre (note: only half of the total acres are harvested in one year).

2.2.2.4 Biofuel Scenarios 2, 3, 4 and 5

Ethanol Production

The scenario calculations estimate biofuel production as ethanol and the electricity production from harvested biomass (see Appendix for details). There are other possibilities for liquid biofuels besides ethanol, such as diesel, jet fuel and other hydrocarbons, but these are conversion technologies are not yet commercial. Ethanol can be created at commercial scale today using starches and sugars as feedstocks, and this present analysis assumes these 'conventional' conversion technologies for sugar cane, sweet sorghum, and cassava. Any cellulosic and fibrous material from these plants is assumed left on the field (for soil quality) or burned for electricity and heat production. This study does, however, compare ethanol production from banagrass, a cellulosic (not starch or sugar) feedstock, even though cellulosic conversion technologies are still under development. To be clear, this study uses ethanol as a proxy for biofuels to enable comparison of feedstock efficacy, not as a commercial recommendation.

Table 4 shows the results that calculate ethanol production is highest from banagrass (1,640 gal/acre, not yet commercial) followed in decreasing order by the 'improved' yield estimate for cassava (30 tonnes fresh weight/acre → 1,500 gal/acre), sugar cane (1,200 gal/acre), 'standard' yield for cassava (20 tonnes fresh weight/acre → 1,000 gal/acre), and finally sweet sorghum (440 gal/acre). The 'standard' cassava yield is representative of what has been produced at existing cassava farming operations, whereas the 'improved' cassava yield represents a value anticipated by Ulupono Initiative. The assumptions for yield for sweet sorghum are based on recent crop trials that did not show promising yields (Hashimoto, 2012) (personal communications with Andrew Hashimoto and Richard Ogoshi).

Sugar cane grown on 23,000 acres could produce ethanol with 32% of the energy content of all gasoline consumed on Maui. For banagrass this percentage is 43%, for cassava 40% and 26% (for 'improved' and 'standard' yields, respectively), and for sorghum it is 12%. Thus, even with existing ethanol production technology and feedstocks, Maui can substitute over one quarter of its gasoline needs. Consuming this quantity of ethanol on Maui itself would require changes in vehicle stock to be able to consume this high quantity of ethanol (e.g. greater than 10%-15% blend in conventional gasoline internal combustion engines). In addition, ethanol-to-jet technologies have recently been certified for civilian aviation, which could easily absorb all of the ethanol produced on Maui. If 20–40 Mgal/yr of ethanol were produced on Maui, larger considerations of sustainability and commercial business practices could help determine if the most holistic option would be to consume the ethanol on Maui, ship the ethanol to Oahu for statewide blending, or export the ethanol to mainland U.S. as a low-carbon fuel.

Electricity Production (gross)

Table 4 shows the gross electricity production from each biofuel feedstock is inversely related to its ethanol production. That is to say, given the assumption that only sugars and starches are converted to ethanol (same assumption does not hold for banagrass since it has no sugars), a feedstock with higher fiber content produces a higher fraction of electricity relative to ethanol. Sweet sorghum produces more fiber (fewer sugars) per tonne of crop biomass, and thus enables the highest gross electricity production (120 GWh/yr) followed by banagrass and sugar cane (similar gross electricity of 95 and 86 GWh/yr, respectively) and finally cassava (41 and 62 GWh/yr for the 'standard' and 'improved' yield, respectively). Most of the cassava plant is starch in the root versus fibers in the peels, stems, and leaves. None of the analysis of electricity production assumes that leaves from any crop are harvested and used for electricity. All leaves are assumed burned or left on the field for soil fertility. See Appendix for more detailed assumptions for electricity production from each crop.

The gross electricity production from the 23,000 acre biofuel scenarios, as a proportion of total estimated electricity generation (from Table 3) on Maui, is 6.3% (sugar cane), 8.8% (sweet sorghum), 3.0% and 4.6% (cassava 'standard' yield and 'improved' yield, respectively), and 7.0% (banagrass).

Electricity Production (net)

There are many factors that go into the design of a biorefinery for producing ethanol, and potentially excess, or 'net', electricity that is exported from the mill to the electric grid. As this present analysis is primarily focused on water, liquid biofuels, and food, it does not describe or analyze the details related to biorefinery design and handling of different types of biomass from the crops (e.g. fiber from stems, fiber from leaves or trash, etc.). One life cycle assessment of Brazilian sugar cane to ethanol mills suggests that the average mill produces net electricity ranging from 0%–25% of its total consumption of approximately 30 kWh per tonne of sugar cane (kWh/tc) (Macedo et al., 2008). The authors of this Brazilian study then go to consider a future scenario (in the year 2020) where 40% of all sugar cane trash is collected and burned to produce net electricity of 135 kWh/tc by using new high pressure (6.5 MPa) and temperature (480 ^{o}C) boilers. Thus, this 135 kWh/tc net electricity is 82% of the total gross electricity generation.

For this study, the range of net biomass electricity from each biofuel feedstock scenario, except cassava, is assumed from 0%–40% of the gross electricity. For cassava, an upper range of 8% is set for the proportion of gross electricity that can be exported to the grid (personal communication with Ulupono Initiative). At 0%, there can be no revenues for selling electricity, and at 40% of gross electricity sold via the electric grid, there can be significant revenues (see Figure 20 and Figure 21). These electricity revenues must be considered in the context of the capital costs for building a biorefinery that enables the electricity export, and that analysis is beyond the scope of this report.

2.2.2.5 Food Scenarios 6 and 7

The production estimates for beef, milk, and diversified agriculture (fruits and vegetables) provide very significant fractions of total consumption on Maui. The 3.7 million gallons of *net* milk produced from cattle on 782 acres (13%) of the 5,850 acres of pasture fulfills all of estimated Maui milk consumption. The 1,850 short tons of *net* beef production (sales by cattle rancher) on 5,070 acres provides 40% of Maui beef consumption. Note that the baseline estimate of beef production on Maui equates to approximately 1% of current Maui consumption, so that total Maui beef production for the pasture scenario provides 41% of Maui consumption. It is important to consider this grass-fed beef and milk scenario as but one option to produce protein and dairy products on Maui.

As mentioned previously in Section 2.2.1.6, the diversified agriculture scenario assumes a crop mix of bananas, lettuce, cabbage, and onions. These crops are only meant to be generally representative of the fruits and vegetables that can be and are grown on Maui in order to get an estimate of water needs. There are many other viable crop choices that could be and are currently grown: coffee, pineapple, nuts, etc. The modeled production of the diversified agriculture crops are shown in Table 6. The sum of production of these crops is 14,200 tonnes/year, and at an assumed loss rate of 16%, is estimated as 11,900 tonnes/yr of *delivered* fruits and vegetables compared to 3,600 tonnes that are estimated delivered in the baseline current situation (see Table 3). The baseline scenario delivers 16% of Maui fruits and vegetables consumption, and the diversified agriculture scenario delivers 69%.

Table 6. Diversified agriculture yields and number of crop harvests per year (CTAHR, 2008, USDA, 2011).

	Dry Onions (two crops per year)	Bananas (one crop per year)	Cabbage (two crops per year)	Lettuce (two crops per year)
Yield per crop (lbs/acre/harvest)	13,000	17,000	30,000	11,000
Yield per crop (tonnes/acre/harvest)	5.9	7.7	13.6	5.0

2.2.2.6 Summary of System Energy and Food Scenarios

The system energy and food scenarios combine the food production of the Pasture and Diversified Agriculture scenarios with each biofuel scenario.

Figure 18 and Figure 19 show five metrics of interest for comparing the scenarios of this analysis:

- Liquid Fuels – The percentage of Maui's gasoline (liquid) fuel energy (on an energy basis) consumption that could be served by ethanol (liquid) production.
- Gross Electricity as Renewables – The percentage of gross electricity production on Maui (in kWh) that can be served by all renewable electricity generation on Maui that includes biomass electricity from biofuel crops *and* existing Maui wind and hydroelectric power.
- Fruit and Vegetables – The percentage of Maui fruit and vegetable consumption (by mass) that is provided by the Diversified Agriculture scenario *and* the estimate of existing Maui diversified agriculture production.
- Beef – The percentage of Maui beef consumption (by mass) that is provided by the Pasture scenario *and* the estimate of existing Maui beef production.
- Milk – The percentage of Maui milk consumption (by volume) that is provided by the Pasture scenario *and* the estimate of existing Maui milk production.

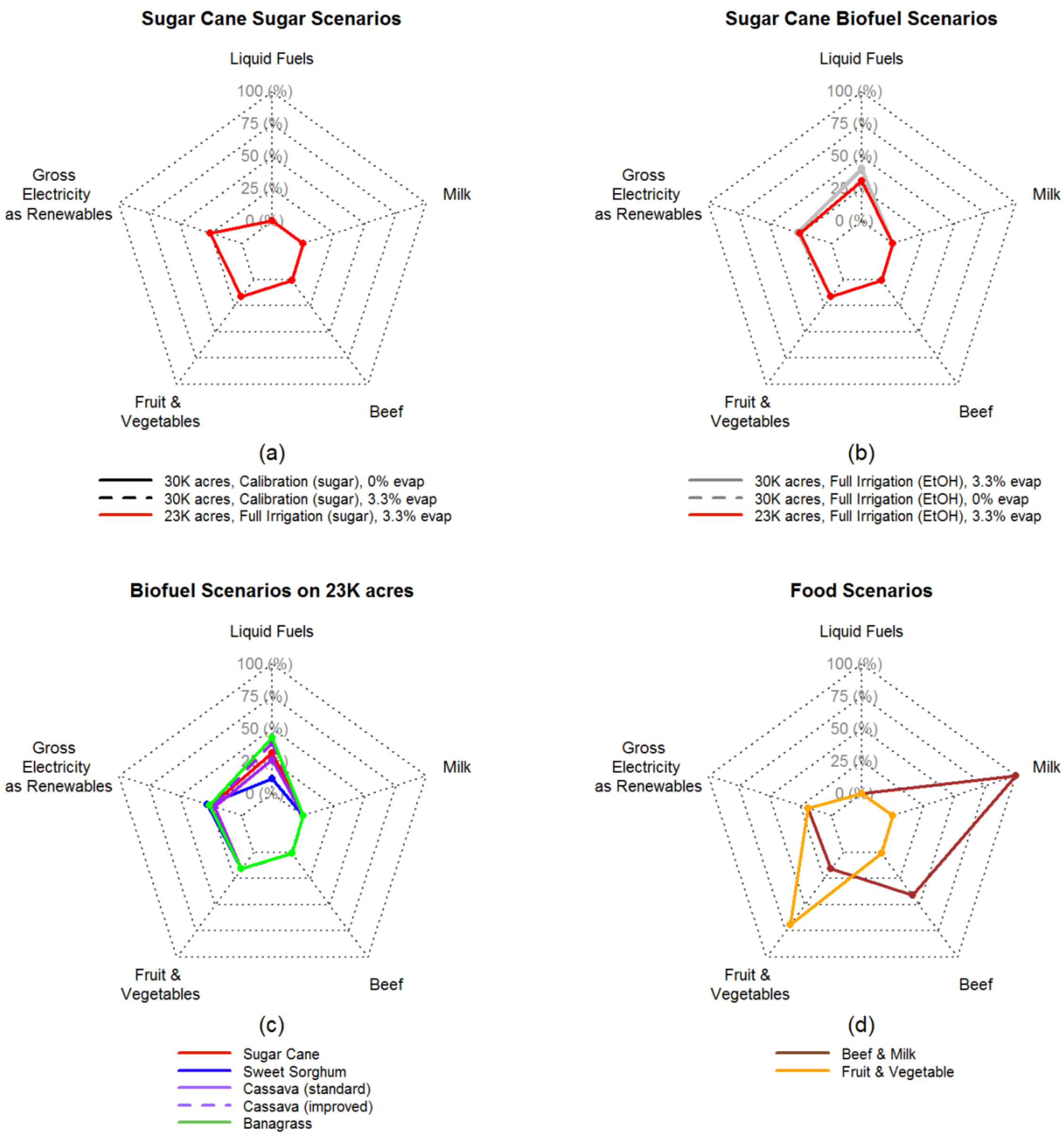


Figure 18. Maui production relative to consumption of each of five metrics for the individual scenarios leading up to the combined energy and food scenarios: (a) the calibration scenarios that produce sugar and molasses as primary products (not shown), (b) biofuel production from sugar cane crops of both 30,000 and 23,000 acres, (c) all biofuel scenarios indicated on the same graphic, and (d) the Pasture (Beef & Milk) and Diversified Agriculture scenarios indicating each of their respective contribution to food production.

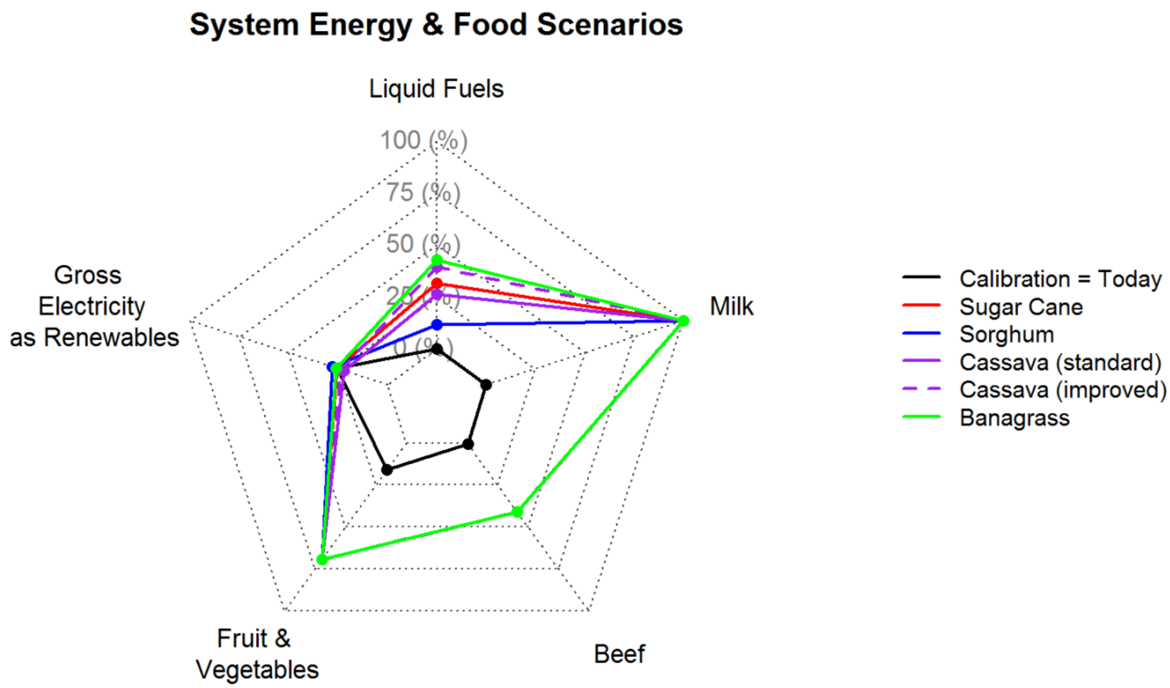


Figure 19. Maui production relative to consumption for each of five metrics for the combined 'system' energy and food scenarios. All system scenarios, by their definition, meet the same percentage of local milk, beef, and fruits & vegetables.

The results in Figure 18(a) indicate that the current situation on Maui provides no liquid fuels, a low percentage of Maui's fruits and vegetables, a significant share of gross electricity production from renewable supplies, and practically no beef and milk. Sugar and molasses production, not shown in Figure 18, are significant contributors to Maui's economy in both revenue and employment. The 'system' scenarios reach a larger proportion of Hawaii's, Maui's, and Ulupono Initiative's sustainability goals in terms of both energy and food production. As discussed in Section 2.2.1, these significant contributions to food and energy self-sufficiency can occur with existing or reduced water consumption. Particularly with cassava, it is unknown whether it can be planted at large scale on Maui, and crop trials would need to confirm harvesting methods, yields, and if the soils and rocks in the soil permit feasible harvesting.

2.2.2.7 Revenues and Water Costs of Scenarios

This section compares each scenario by revenues and water costs (electricity costs of pumping groundwater used for irrigation). Table 7 lists the assumed unit prices of the commodities that are sold within the scenarios. The revenue and water cost calculations assume the same price of electricity sold and consumed for groundwater pumping.

Figure 20 shows the "irrigation efficacy" for each scenario, defined as the revenues per 1000 gallons of irrigation water (left axis). The higher this metric, the more economic value per applied water, and the better the scenario (all other things equal). If rainfall met the full water needs of the crops, this metric would be infinite.

Revenues are from selling food and agricultural products (sugar, molasses, fruits, vegetables, beef, and milk), ethanol, possibly excess electricity from sugar or biofuel production, and Renew. Recall (see Section 2.2.2.4) that net electricity sales from a sugar or ethanol biorefinery are dependent upon the design and capital investments required (e.g. high pressure boilers) to produce more electricity (and heat) than is needed for the biorefining processes (Macedo et al., 2008, Seabra et al., 2011). Thus, the reader should view the *net electricity* revenues in Figure 20 and Figure 21 as an estimated upper bound, with the lower bound being zero revenues from net electricity.

Similarly, the reader should consider revenues from sales of Renewable Identification Number (RIN) credits as near an upper bound with a lower bound of zero. RIN prices are variable based upon a market induced by government regulation (the Renewable Fuels Standard mandating biofuel production volumes). RIN prices increased considerably in 2013. The assumed RIN price in Table 7 (estimate of April to May 2013 price) is for the "advanced" biofuel category that loosely correlates to biofuels (e.g. ethanol) made from feedstocks other than corn grain. Sugar cane-derived ethanol imported into the U.S. from Brazil also counts as an advanced biofuel, as the definition of "advanced" biofuel relates to its life cycle greenhouse gas emissions relative to conventional gasoline (EPA, 2010). All of the biofuels modeled in this report are assumed to qualify as advanced biofuels under the RFS.

Table 7. The assumed unit sales prices for agricultural and energy products.

Item	Unit price	Units
Sugar	545	\$/tonne
Molasses	109[a]	\$/tonne
Net electricity (to grid)	0.17[b]	\$/kWh
Ethanol	2.74[c]	\$/gallon
Renewable Identification Number, "advanced" biofuel (RIN)	0.83[d]	\$/gallon
Milk	2.46	\$/gallon
Beef	1.40	\$/lb
Dry onions	1.25	\$/lb
Lettuce	1.9	\$/lb
Bananas	0.6	\$/lb
Cabbage	0.3	\$/lb

a: Molasses is assumed 20% of sugar price by weight (Alexander & Baldwin, 2011).
b: "Commercial" or "wholesale" electricity price at half of nominal Maui retail price of electricity of \$0.34/kWh.
c: 30-day average price (May 15, 2013) of ethanol in continental United States (Bloomberg) plus \$0.21/gallon transport cost to Oahu.
d: 30-day average price of advanced biofuel RIN (May 15, 2013) in continental United States (Bloomberg).

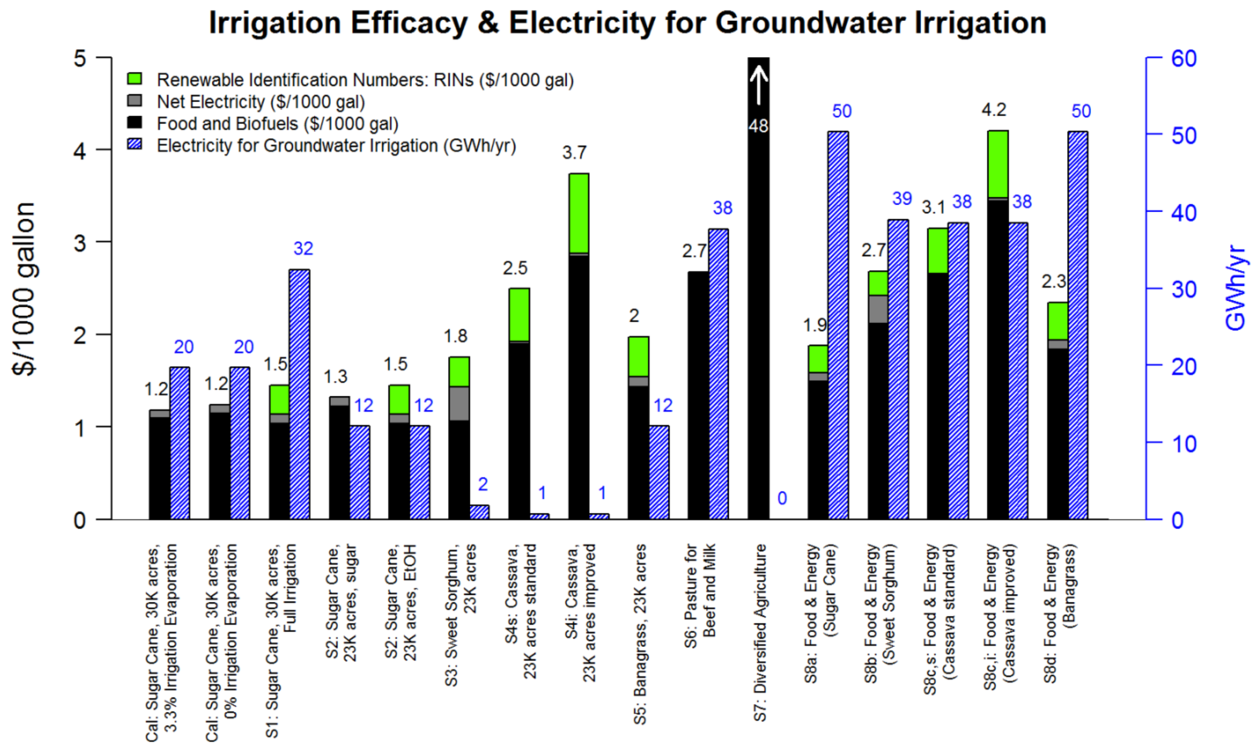
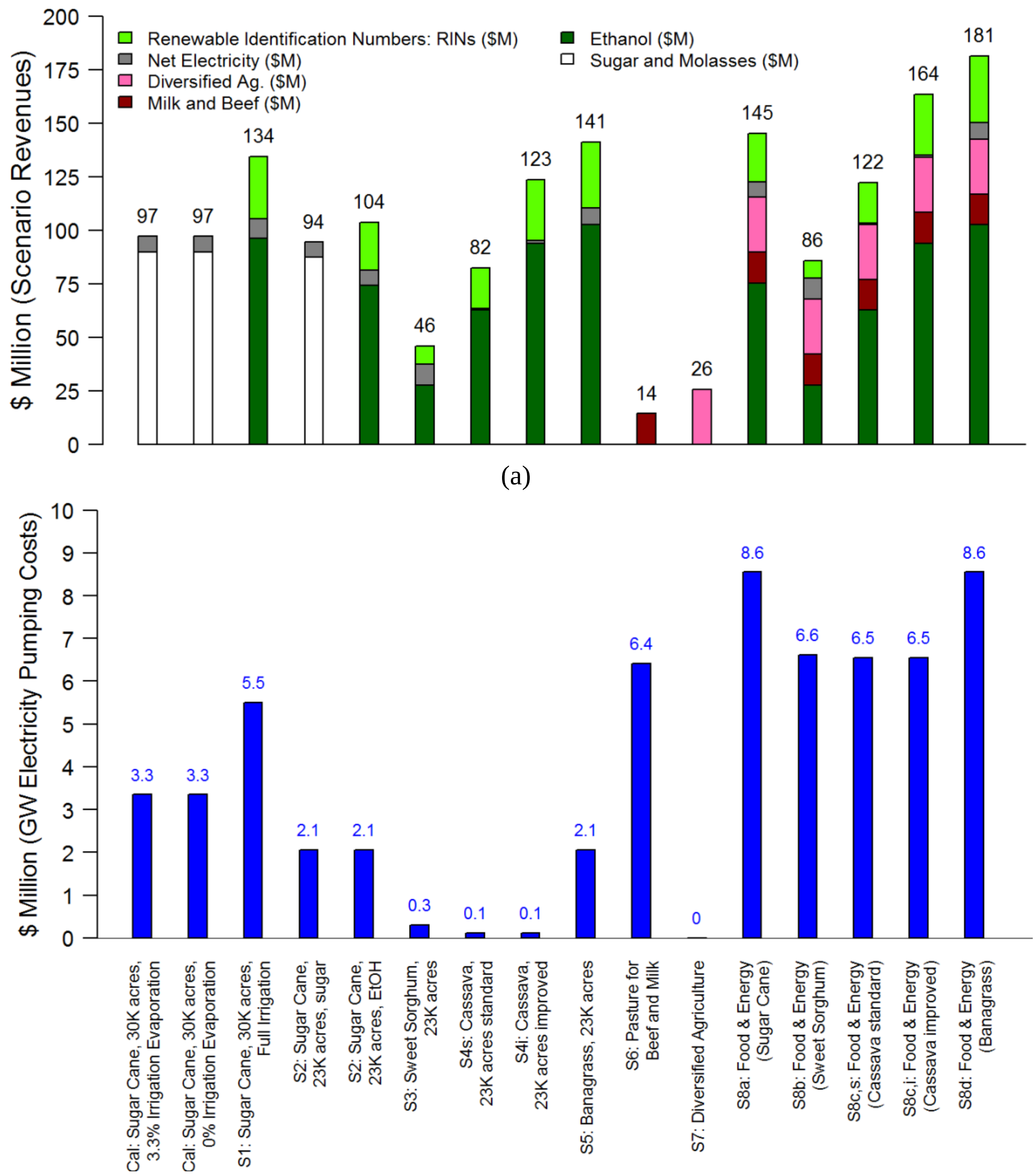


Figure 20. Left columns/left axis: The irrigation "efficacy" of the different scenarios is the estimated revenue ($, dollars) per 1000 gallons of irrigation water. Revenues can occur from selling the agricultural products (sugar, molasses, fruits & vegetables, beef, and milk), selling Renewable Identification Number (RIN) certificates for biofuels, and selling electricity to the Maui grid. The revenues from selling 40% of gross biomass electricity to the grid should be considered an *upper bound, with a lower bound of 0%*. Right columns/right axis: Aside from the 'whole-system' scenarios, the electricity for obtaining groundwater for irrigation is highest for Scenario 1 (30K acres of sugar cane at full irrigation) and Scenario 6 (pasture for grass-fed cattle) as it assumes pumping to the high elevation of the Upcountry.

For context, it is interesting to compare the costs and quantity of electricity for water pumping for the scenarios with that of the Maui Department of Water Supply (DWS) (see Figure 6 for DWS water supply volumes). Maui DWS consumes approximately 59 GWh/yr for operations including water and wastewater distribution, wastewater treatment, and groundwater pumping. Groundwater pumping accounts for 32 GWh/yr. This total estimate of electricity for the DWS water supply is three times the electricity for groundwater pumping for the "calibration" scenarios representing sugar cane production today. Assuming that DWS pays a 'commercial' electricity rate equal to half the current Maui island $0.34/kWh retail cost of electricity, DWS would spend $10 million/yr on electricity, approximately half of that expense for groundwater extraction.

Figure 21 shows the total estimated revenues from sale of each commodity (left axis) and costs of groundwater pumping for irrigation (right axis) for each scenario. Note the left and right axes have significantly different scales but the same units. The calculated results in Figure 21 do not imply that $0.17/kWh *is* the price that HC&S or any other agricultural producer pays for electricity, but this price is a proxy for the wholesale or opportunity cost of generating that electricity. Today, HC&S generates more electricity (from coal, biomass, and hydropower) than it consumes, even when including the electricity for groundwater pumping (see Figure 20).



(b)

Figure 21. (a): Annual revenues ($ millions) from the sale of agricultural products, biofuels, RINs, and possible net electricity for each scenario; (b) the annual electricity cost ($ millions) of pumping groundwater for crop irrigation (see Figure 20) at a rate of $0.17/kWh.

Plotting revenues and water costs provides some context to the energy-water nexus: pumping water requires energy to produce crops that are converted to fuels and electricity. The pumping electricity and costs are dominated by the assumption of irrigating pasture grass with water from the Makawao aquifer (assumed at sea level) from an average elevation of 2,650 feet above sea level for Land Parcel 16. This pumping necessitates 8,300 kWh per million gallons (kWh/MG) at theoretical minimum (see Appendix Section 1.2.1.2), and this report assumes pumping to occur at 9,000 kWh/MG. For all energy and food system scenarios, the cost of groundwater extraction is 10% or less (10% for Scenario 8b: Sweet Sorghum) of estimated revenues.

One might think it feasible to pump water to Land Parcel 16 (for irrigated pasture) from the highest elevation HC&S surface water ditch to avoid some of the electricity cost of pumping from the Makawao aquifer. The highest HC&S irrigation ditch in Central Maui near Land Parcel 16 is Hamakua at approximately 1,100 feet in elevation. Thus, pumping from 1,100 feet to 2,650 feet needs less electricity: 4,900 kWh/MG theoretical minimum, approximately 3,400 kWh/MG less. The agricultural operation could maximize ditch flows to the higher elevations of HC&S lands (in the range of 500−1,100 foot elevation), as largely practiced by HC&S already, and groundwater pumping for the lower elevation parcels (0−500 foot elevation). This coordination could avoid perhaps < 1000 feet of pumping elevation for the 5.4 BGY of irrigation for pasture on Land Parcel 16, thus only minimizing pumping energy intensity by maximum of ~ 3,400 kWh/MG.

This act of pumping surface water to high elevation pasture could save electricity; however in observing Figure 14 of the monthly water flows for the system scenarios, the highest water demands are in the summer when ditch flow is not sufficient to irrigate all crops. Thus, saving some ditch water to pump to Land Parcel 16 (from 1,100 to 2,650 feet) to avoid pumping from the Makawao aquifer necessitates that *more* groundwater is needed to pump to some HC&S land parcels from one of the Central Maui aquifers that would put them closer to unsustainable groundwater extraction. The good news is that each Central Maui biofuel scenario (Figure 8 - Figure 11) already has some net groundwater recharge such that there could be some substitution of groundwater for surface water without a net depletion. The energy and food 'system' scenarios fo cassava and sorghum are more feasible than the sugar cane or banagrass scenarios because they both have an overall net recharge from irrigation (as modeled). In all cases the *net recharge decreases* once one replaces surface water irrigation with groundwater irrigation. A more detailed study is needed to estimate the costs and benefits of using EMI ditch surface water for Upcountry irrigation. Due to electricity pumping costs, the assumption of significant irrigation in Upcountry Maui places pressure on the economics of any agricultural operations.

2.3 Drought Scenario: Reduced Surface Water Delivery

During discussions with stakeholders and subject matter experts while performing the studies in this report, many of the stakeholders expressed a desire to have a future climate and/or drought scenario. Here a drought scenario is defined by assuming EMI ditch flows of 1962 (based upon the average monthly flows in the Wailoa ditch). Lower EMI ditch flows translate to lower surface water availability for crops in Central Maui.

Lower surface water diversion into the EMI system translates to increased groundwater pumping to irrigate crops *if* crops are to be provided all water for total evapotranspiration needs. Figure 22 shows the monthly water balance for the four 'system' Energy & Food scenarios when assuming an estimate of the lower EMI ditch flows of 1962. Compared to the results for average ditch inflows in Figure 14, these low flow scenarios require larger quantities of groundwater extraction, particularly in the summer months. The 1962 Wailoa ditch flow is lower than the average Wailoa ditch flow for all months except March. The estimated annual surface water delivery from the EMI system in the average year is 58 Bgal/yr versus 42 Bgal/yr (28% less than average) for estimated 1962 deliveries (see Table 8). The energy and food production is assumed the same as in the scenarios with average EMI ditch flows.

Table 8. The estimated 1962 total EMI surface water delivery is 16 Bgal/yr less than in the average year.

Flow Regime	Monthly Flow Rates (Mgal/d)												Annual flow (Bgal/yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1962	78	73	237	141	145	53	130	140	110	77	75	118	42
Avg.	129	125	178	198	188	142	179	177	127	138	169	154	58

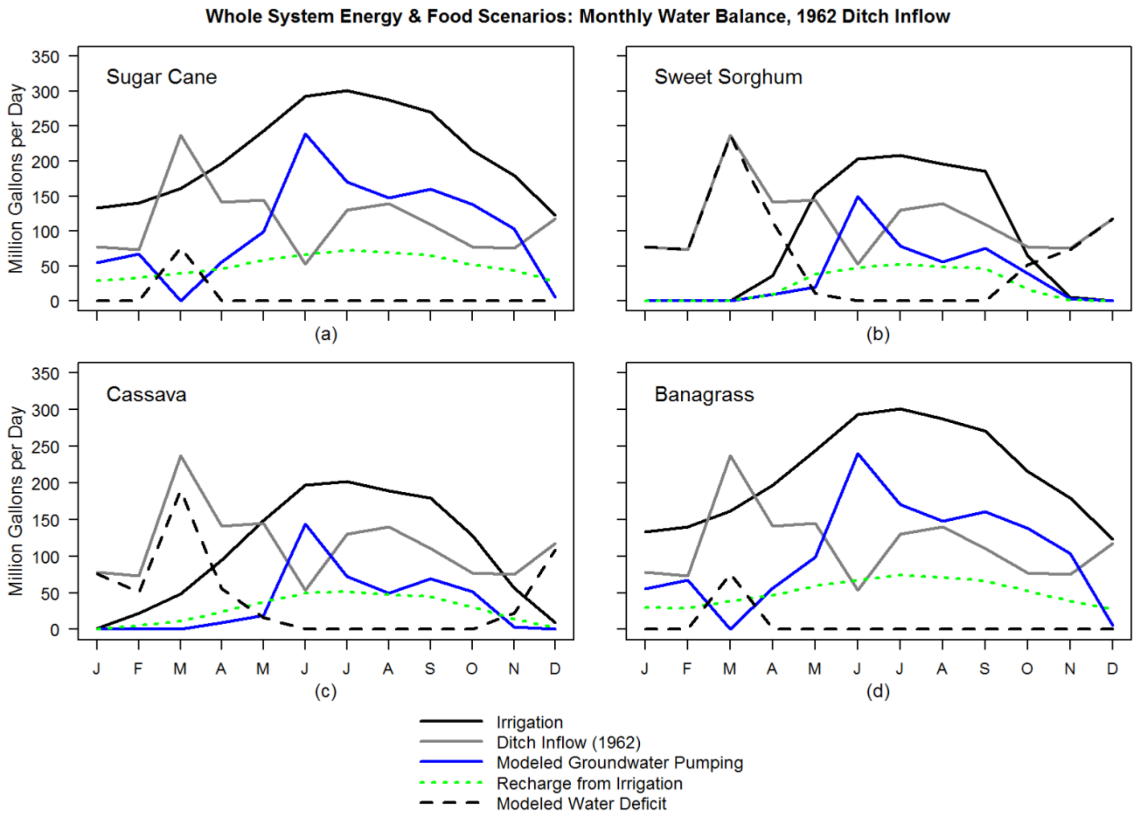


Figure 22. The *monthly* water balances, assuming estimated *1962 EMI ditch inflows*, for the four 'system' energy and food scenarios using biofuel feedstocks of (a) sugar cane, (b) sweet sorghum, (c) cassava, and (d) banagrass. The 1962 EMI system inflows are estimated from USGS stream gauge 16588000 (Wailoa) data from 1962.

The net impact of low ditch inflows is that significantly larger groundwater extraction is needed to fulfill crop water needs as compared to the average ditch inflow situation. Figure 23 shows *total* groundwater extraction and *net* groundwater extraction for each biofuel and "Energy & Food" scenario using two assumptions: average EMI ditch inflows and low EMI ditch inflows based on 1962 monthly Wailoa ditch flows. Figure 23 repeats the groundwater extraction information from Figure 16 while comparing total groundwater extraction and net groundwater extraction for the "low" ditch flow (1962 Wailoa flows) scenario. In both cases, the crop water needs and rainfall in Central Maui are assumed identical, but weather patterns that create low rainfall in northeast Maui might cause greater or lower rainfall in Central Maui. Figure 17 of (Engott and Vana, 2007) shows that in 1962 the rainfall on West and Central Maui was just above 70% of the authors' calculated average rainfall over the rain gauge data period from 1926-2004. Thus, it is feasible to surmise that in 1962 there was low rainfall in both the windward northeaster side of Maui (indicated by low EMI ditch flows) and Central Maui (indicated by rainfall calculations by (Engott and Vana, 2007)).

Figure 23 indicates that unsustainable groundwater extraction during average EMI flow years becomes even more so during a year of lower ditch inflows. The sugar cane and banagrass biofuel-only scenarios have significant groundwater depletion under the 1962 low-flow situation, but the sweet sorghum and cassava biofuel scenarios are both near zero in terms of net groundwater extraction. Cassava could be a good drought-resistant crop. Because this model assumes the water consumption for sweet sorghum is associated with significantly low yield, it is not prudent to conclude sweet sorghum produces significant yields *with* low water consumption. Just as in the average EMI flow situation, the combined energy and food scenarios trend toward higher overall net groundwater extraction (or lower net groundwater recharge) because of the assumption of 100% groundwater for irrigating Upcountry pasture.

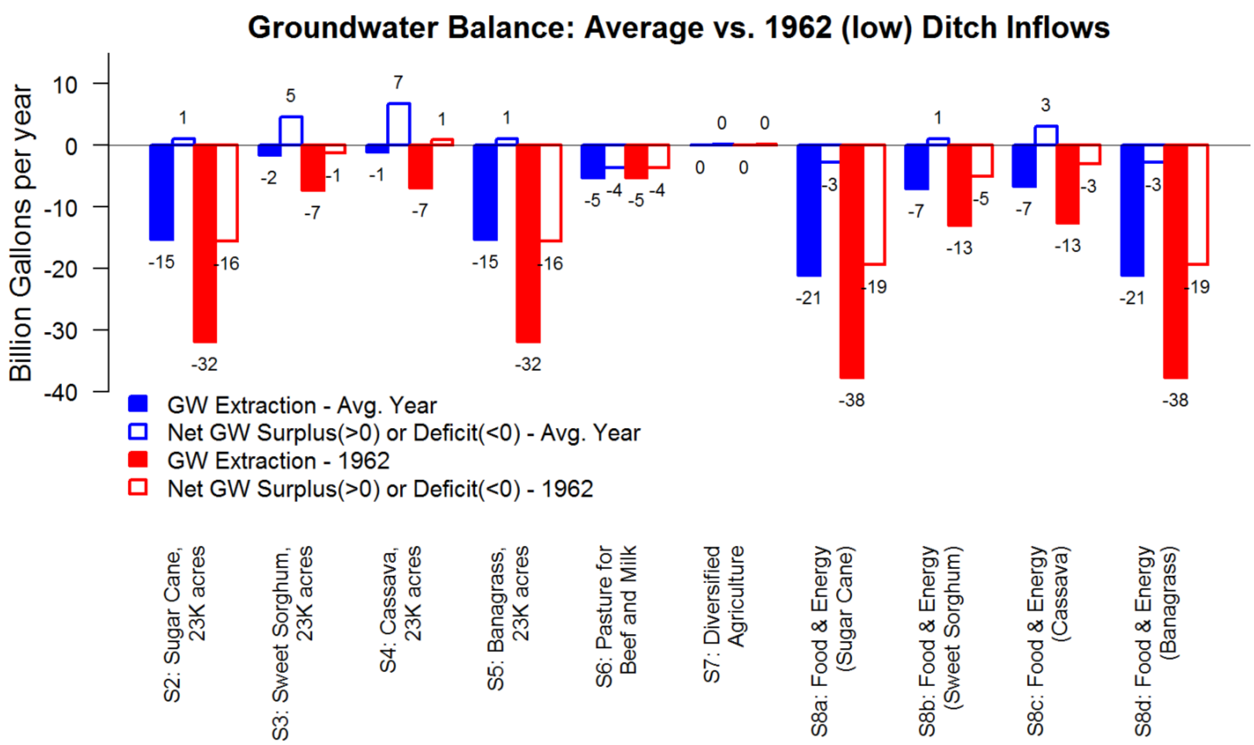


Figure 23. The lower ditch inflows estimated from the 1962 low-flows (monthly) in the Wailoa ditch would necessitate much higher groundwater pumping for all scenarios due to lower surface water deliveries. The modeling indicates that the sweet sorghum and cassava scenarios could still have near zero net groundwater extraction in a year with very low ditch inflows.

Strangely, the year 1962 does not appear to be a year of significantly low rainfall in Hawaii overall (Diaz and Giambelluca, 2012), and neither an El Niño nor La Niña phase of ENSO are strongly active. However, 1962 seems to occur during the middle of a three-decade negative PDO phase, with negative PDO trends associated with higher rainfall, at least prior to 1980 (Diaz and Giambelluca, 2012). Post 1980, the negative correlation of PDO index to rainfall seems to have weakened, but even for the pre-1980 time period, the correlation was less strong for Maui than the other islands (Diaz and Giambelluca, 2012). Some analysis suggests that global warming trends might be responsible for the weaker PDO to Hawaii winter rainfall relationship, but further scientific studies could better determine the correlation of rainfall in Northeast Maui to Central Maui as they relate to climate change (global warming) and oceanic decadal trends.

3. Perspectives on Water Supplies and Demand

3.1 Watershed Management

The Hawaii residents and government understand the benefits of maintaining quality watersheds that enable the capture of precipitation and fog drip while enabling that moisture to percolate into groundwater and collect in streams. The Hawaii Department of Land and Natural Resources (DLNR) is tasked to ensure 'mauka', or upland, watersheds are fully functioning so fresh water resources can be utilized and enjoyed by the people of Hawaii in perpetuity. *The Rain Follows the Forest* is the DLNR's plan to implement the goal of protecting watersheds. The East Maui Watershed Partnership (EMWP) was formed for East Maui to protect that watershed, and EMWP includes landowners with over 100,000 acres. The EMWP exists to preserve the streamflows upon which the scenarios of this report depend. With lower streamflows, there is less surface water that can be diverted into irrigation ditches or reside in streams for environmental and cultural uses.

In preserving the watershed, the EMWP and others engage in various activities meant to stabilize, increase, and improve Maui's water supplies by:

- Minimizing soil erosion to prevent negative impacts to streams, water supplies, and near-shore reefs,
- Preserving island biodiversity and its unique flora and fauna, and
- Educating an informed public.

Much of the investments in the watershed are meant to remove ungluates (mostly pigs and deer) that eat or otherwise destroy (by trampling) native vegetation and spread invasive species. This native vegetation has evolved to hold soil in place, collect and store precipitation, and reduce evapotranspiration of exposed soils (Loppe and Kraftsow, 2001). Fencing and hunting programs help control ungulate populations.

It is also important to remove invasive plant species that reduce the ability of the native forest to provide the ecosystem services related to water resources (Gutrich and Donovan, 2001). Alien and invasive plant species can outcompete or shade native plants to change forest competition that can reduce these services. Two of the invasive plants that have been studied are *Miconia calvescens* (a shrubby tree that threatens moist tropical watersheds in Hawaii) and Strawberry Guava.

In a study investigating the optimal control of *Miconia calvescens* in the Hawaiian Islands, Burnett et al. (2007) estimated that *Miconia*, allowed to cover its potential habitat (areas with > 1,800 mm/yr of rainfall), could cause between 3.7 and 4.6 MGD of lost aquifer recharge on Maui (Burnett et al., 2007)[7]. The potential carrying capacity of *Miconia* was thus estimated at 14 million trees on 14,000 acres (100 trees per acre). Most of this potential *Miconia* habitat is on the northeast side of East Maui and the high elevations of West Maui. Accounting for this reduced aquifer recharge and a loose estimate of the loss of half of 17 bird species[8] on Maui (if *Miconia* covered its entire possible habitat), Burnett et al. (2007) estimate economic damages of 78–187 $ million/yr if *Miconia* extended to 14 million trees from their estimated existing population of 110,000 trees.

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[7] Also see: http://www2.hawaii.edu/~kburnett/JFE.pdf.

[8] Burnett et al. (2007) use assume every Hawaiian household would be willing to pay $31/yr/bird species to prevent extinction Loomis, J. B. & White, D. S. (1996) Economic benefits of rare and endangered species: Summary and meta-analysis. *Ecological Economics*, 18**,** 197-206..Loomis, J. B. & White, D. S. (1996) Economic benefits of rare and endangered species: Summary and meta-analysis. *Ecological Economics,* 18**,** 197-206.

In estimating the optimal quantity of *Miconia* on Maui, Burnett et al. (2007) accounted for the cost of finding and eradicating *Miconia* and the economic benefits of eradication. It does not make pure economic sense to eradicate the last few trees because the cost of finding and eradicating them is much higher than the benefits gained from removal. Thus, there exists an 'optimal' theoretical quantity of invasive trees that can be maintained at steady state (tree population does not expand or shrink) where the marginal costs of eradication and damages equal marginal opportunity costs of maintaining that population (Burnett et al., 2007). For Maui, Burnett et al. (2007) estimate this optimal steady state *Miconia* population on Maui as 9,000–19,000 from their estimated existing population of 110,000. Reducing the population to its optimal value is suggested to have $35 million in present value benefits (the study was performed sometime after 2005) when spending more than the current (at the time) $1 million/yr in control efforts. Even assuming the high estimate (4.6 MGD) of recharge losses due to a "complete accommodation" of *Miconia*, this is a very small portion of Maui's groundwater resources (see Figure 2), particularly on the windward side of Maui. However, this quantity represents 40% of Central Maui's (Department of Water Services Central District) projected increase in water demand from 23 MGD in 2010 to 34 MGD in 2030 (DWS, 2010).

In addition to maintaining healthy forests for watershed management that enables groundwater recharge and increased forest biodiversity, the water storage and precipitation collection services increase base surface water streamflows while mitigating variability. A good base streamflow is valuable for growing taro in the lowland regions while also feeding into fish ponds in the coastal areas. The traditional method of growing taro involves a succession of terraced pond in which water flows form one pond to the next. This water, temporarily diverted from the stream, maintains the correct temperature of the ponds only if there is a sufficient flow rate. Thus, low flows in streams can be insufficient for supporting wetland taro farming. Other taro varieties can be grown on dry land as opposed to ponds.

While the general benefits of watershed management are known, the specific benefits and required investments for the watersheds of Northeast and Central Maui are unknown. Despite existing efforts to remove ungulates and invasive vegetation, discussions with stakeholders revealed that there very little is known. This lack of knowledge makes it difficult to prioritize efforts of watershed protection versus other options for water conservation and new supplies.

3.2 Municipal Water Supply and Demand

The Maui DWS Water Use and Development Plan (WUDP) for Central Maui compares six candidate water strategies on a suite of "planning objectives" and economics (DWS, 2010). The baseline assumption of the report is an increase in Maui DWS Central District water demand from 23 MGD in 2010 to 34 MGD in 2030 (base case). This 11 MGD increase over 20 years compares to the estimate of approximately 42 MGD of total municipal water demand on Maui (see Figure 6). Thus, the additional 11 MGD of demand is a significant increase relative to current consumption on the entire island, not only the Central Maui area.

The WUDP candidate strategies represent vetted options for matching water supply and demand over the short and long term. Table 9 lists the planning objectives as developed by the Central District Water Advisory Committee. The six evaluated candidate strategies are:

1. Northward basal well development (groundwater on northern portion of West Maui)
2. Haiku aquifer well development (groundwater wells near Haiku)
3. Extensive conservation and recycling (demand side management of water use and treatment of wastewater to R1 standards, or tertiary treated recycled water that can be used without restrictions)
4. Na Wai Eha surface water treatment (use Na Wai Eha as surface water supply)
5. Na Wai Eha surface water treatment with large raw water storage reservoir
6. Brackish water desalination

Table 9. List of planning objectives in Maui DWS Water Use and Development Plan

Objective	**Description**
Availability	Provide Adequate Volume of Water Supply
DHHL	Provide For Department of Hawaiian Homelands Needs
Agriculture	Provide For Agricultural Needs
Cost	Minimize Cost of Water Supply
Efficiency	Maximize Efficiency of Water Use
Environment	Minimize Adverse Environmental Impacts
Resources	Protect Water Resources
Streams	Protect and Restore Streams
Culture	Protect Cultural Resources
Quality	Maximize Water Quality
Reliability	Maximize Reliability of Water Service
Equity	Manage Water Equitably
Sustainability	Maintain Sustainable Resources
Conformity	Maintain Consistency with General and Community Plans

Of the six candidate project concepts, the conservation and recycling water strategy was assessed to have positive impacts for nine of the planning objectives, require caution for one objective (environment – mainly for construction-related impacts), and not rated for the other five of the planning objectives. Interestingly, all candidate strategies were rated as needing “caution” with regard to overall environmental impacts. All five of the other (not conservation and recycling) strategies were rated in as having a negative impact for at least one planning objective. Many of the ratings for caution or negative impacts related to increased energy usage for pumping groundwater, and particularly for the desalination strategy. It is important to note, that recycling wastewater to R1 levels also requires additional energy use - an additional 340 kWh/million gallons for R1 treatment (see Appendix). This compares to the need of 3,500 – 10,000 kWh/million gallons for brackish water desalination (King et al., 2008, Stillwell et al., 2011).

Under the main set of economic assumptions, including an oil price of $75/BBL in 2008 (increasing 1%/yr), the 50-year net present value (NPV) of the system costs for each of the six candidate strategies range from approximately 700,000 to 750,000 year 2006 US dollars ($2006) (page 92 of (DWS, 2010)). This price range includes a ‘reference strategy’ to which the candidate strategies are compared. The reference strategy is includes three new wells in the northern half of the Waihee aquifer and three wells in the Kahakuloa aquifer. As stated in the WUDP, relative to the reference strategy, "The revised Northward Basal Groundwater strategy includes twice as many, much smaller wells than the reference strategy and assumes costs that have been updated with more recent information. The revised Northward strategy is more expensive due to higher estimated project costs and lower expected production capability (DWS, 2010)."

The cheapest strategy was the Waiale water treatment plant without water storage (considered potentially not able to provide reliable supply without a storage reservoir). The second cheapest strategy was the one focused on 'extensive' conservation and recycling (assuming investments to capture 45% of the conservation technical potential). When assuming a higher energy price environment, $125/BBL (increasing 1%/yr), the cost rankings are the same as both the cheapest strategies mentioned in this paragraph appear even cheaper on a NPV basis.

3.3 Additional stakeholder questions

In meeting with stakeholders to discuss the context and preliminary results of this research paper, there were many questions that arose but that are beyond the scope of this report. Two of these questions, and their implications, are:

1. Can this type of analysis be reproduced for other locations in Hawaii?

Yes, but the speed and accuracy depend upon *data availability* and the existence of location-specific scientific studies. The Hawaii Rainfall Atlas, with online data and maps, and make rainfall data more available than ever before. Quality stream gauge data are needed to provide realistic scenarios of any diverted streamflows into irrigation ditches, and providing these data is becoming more difficult for organizations, such as the US Geological Survey, due to budget constraints.

The main data that are useful (at least monthly resolution) are rainfall, irrigation ditch flows, crop yields specific to Hawaii, historical water use for agriculture and non-agricultural needs, and maps for current land uses, streams, ditches, aquifers, and soils.

2. What might happen to the assumed 7,000 acres of agricultural land (30,000 acres of sugar cane shifting to 23,000 acres of biofuel feedstocks) that no longer uses plantation crops?

One concern raised by this question relates to whether or not the 7,000 acres would stay in agricultural use, whether actively managed or not. The scenarios presented in this report are not meant to imply the 7,000 acres of agricultural land could not or should not stay in agricultural use (active or not). The stakeholders of Maui can work to find a system solution similar to or different from the scenarios of this report.

There are several possibilities for keeping the 7,000 acres in agriculture. These include continuing production on the full 30,000 acres but with a crop (or mix of crops) that need less water than sugar cane. This could possibly be 30,000 acres of a single low evapotranspiration (ET) crop (e.g. cassava), or some mix of high and low ET crops (e.g. cassava and sugar cane). Some type of forestry might be an option. Of course, mixing crops likely raises costs per output of crops or energy (e.g. ethanol) due to the additional capital and different operations associated with handling both crops.

3. How can you compare biofuel production from conventional feedstocks (sugar cane, cassava, and sweet sorghum) to cellulosic feedstocks (banagrass)?

This point is discussed in Section 2.1 as some subject matter experts suggested to avoid comparing banagrass-based (2^{nd} generation) biofuels to those from 1^{st} generation crops such as sugar cane, sweet sorghum, and cassava. The reason is because conversion of cellulosic feedstocks to liquid fuels is not yet commercial. Further, just as banagrass cellulosic material can be converted to liquid fuels, so can fibrous materials of sugar cane and sweet sorghum. Thus, an energy output analysis could assume cellulosic conversion of all feedstocks with the tradeoffs based upon an economic analysis. Because of general interest in banagrass as a biofuel feedstock in Hawaii, the report includes banagrass.

4. Conclusions and Implications

What did this study reveal?

This study revealed that systems analysis can create powerful new insights. Maui can create triple the economic revenue it gets from each gallon of water, while consuming one third less water than Central Maui uses today. This analysis confirms that a smaller agricultural footprint in Central Maui (23,000 acres versus 30,000 acres) can operate with less water to help achieve several sustainability goals for Hawaii that relate to renewable energy production, local food production, and sustainable use of water resources. If less surface water is needed for agriculture in Central Maui, then 'newly available' surface water could be used for irrigating other lands for food production, the water could remain in streams for purposes of enhancing biodiversity cultural uses of water, and/or the water could be available to deal with potential reductions in future rainfall.

This study revealed that while Maui can use the available water to make significant strides towards society's goals of food and energy security through self-reliance, there are limits and tradeoffs. Grass fed systems in Upcountry Maui consume so much water that likely only a dairy, rather than beef production, would create enough economic value to be justified. For reasons related to Hawaii's climate, not all bioenergy crops might be viable due to lower yields, even with accompanying lower water demand (e.g. sweet sorghum). For promising bioenergy crops like cassava, full scale commercial trials will need to be conducted to validate yield and ability to harvest.

This study revealed that investing in watershed protection and enhancement can be an important element of maintaining water supply in the face of shrinking cloud cover, but we are lacking the scientific research of reforestation watershed impacts, costs, and management.

Further, the least cost water planning, already underway with Maui DWS, revealed that water conservation and recycling are critically important tools for cost effectively stabilizing water demand while accommodating population growth.

Why Hawaii needs to act

The current water use situation is unsustainable, and is likely to suffer a catastrophic failure in the next prolonged drought. The status quo agriculture in Central Maui currently operates at a water deficit with today's average rainfall patterns, but Hawaii rainfall has been decreasing at a rapid rate the last few decades. These declines in rainfall are consistent with expectations from rising temperatures from climate change. Thus, there is the distinct possibility that Hawaii rainfall will continue to decrease in the future. More drought-tolerant and less water-hungry crops will be needed if only to deal with decreased rainfall.

As shown in previous studies (Engott and Vana, 2007), the current amount of groundwater pumping beyond the sustainable yield of the Central Maui aquifers is enabled by the use of East Maui Irrigation surface water contributing to recharge. The results of Scenario 1 (30,000 acres of sugar cane with full irrigation) show that it requires a significant depletion of the aquifers (depletion of 13 billion gallons per year, or 35 million gallons per day). The calibration scenario modeling current groundwater extraction for sugar cane on 30,000 acres shows groundwater extraction is very near that of recharge from irrigation, indicating that suboptimal yields are the tradeoff for maintaining aquifer sustainability.

Overall, 215 GWh/yr (17%) of the electricity demand on Maui is used to pump or move water, which is partially offset by the 7% of Maui's electricity supplied from bagasse biomass. As Maui moves to greater penetration of renewable energy, primarily wind, each successive wind energy plant is experiencing higher levels of curtailment. The prolonged drought extending through 2013 has taken its toll on food agriculture, to the point that the major ranches in East Maui slopes of Haleakala can longer supply cattle for local consumption. The system is already beginning to fail, Maui does not have the luxury of waiting.

What are Maui's Choices?

The system scenarios show that the EMI ditch normally provides more than enough water for all but the summer months. In the drought scenario assuming surface ditch flows as in 1962, the 23,000 acres of cassava is *still modeled to have net groundwater recharge*. The lower water needs of a root crop such as cassava could enable the achievement of multiple sustainability goals, even in drought years and with expectations of declines in rainfall. Crop testing for yields and harvesting techniques are needed to determine the feasibility of growing cassava in Hawaii at commercial scale.

The combined energy and food systems scenarios require 52-64 Gwh/yr of electricity for groundwater pumping, compared to the 20 GWh/yr required for sugarcane today. The total system needs for food are dominated by the assumption of needing 51 GWh/yr for deep pumping from the Makawao aquifer for irrigated beef and dairy pasture. This situation is not likely to be economically viable or ecologically sustainable. By eliminating the beef pasture to focus solely on dairy, the electric consumption drops to 7 Gwh/yr. For 23,000 acres for biofuel feedstock, the lower elevation pumping needs require much less electricity at 1–2 GWh/yr for cassava and sweet sorghum and 12 GWh/yr for sugar cane and banagrass. Therefore, an optimized cassava, diversified agriculture and dairy (no beef) scenario would use only 8 Gwh/yr. Combined with the total electrical demand of Maui DWS (59/GWh/yr), the total electrical demand for water treatment and irrigation pumping would be 69 GWh/yr, or 6% of total Maui 2012 demand of 1,149 GWh. Based on the most recent, integrated resource plan, this could clearly be supplied with the proposed mix of 40-50% renewable energy.

Sugar cane, cassava, and banagrass should be able to produce ethanol to replace a substantial portion, 26%–43%, of gasoline energy consumed on Maui. Due to results from recent poor crop trial results, sweet sorghum needs further study to determine if yields can approach those typical of areas outside of the tropics. While the electricity production from the non-sugar and starch of the biofuel feedstocks produces significant quantities of electricity, this electricity might not be able to contribute to meeting demand on the Maui electric grid. The generation of net electricity depends upon the design and investment in the biofuel biorefinery. For all system scenarios, the cost of groundwater extraction is 10% or less (10% for Scenario 8b: Sweet Sorghum) of estimated system scenario revenues ranging from 82–178 $ million/yr.

A Call to Action

The study points to some immediate actions that would help all the stakeholders in Maui make more informed decisions regarding their water use, and potentially avoid future conflicts over water. The critical needs for scientific and commercial research are:

- Watershed management and restoration to understand costs and hydrological impact
- Aquifer characterization, particularly for the major aquifers affected by ground water pumping and possible
- Pre-commercial bioenergy crop trials on cassava at the scale needed to affirmatively determine yield and harvest requirements
- Integration analysis of use of curtailed wind energy for water pumping in agriculture and municipal systems

Finally, acting on systems recommendations takes cooperation across all stakeholders. This study could not have been accomplished without building on the decades of work done by others, and the cooperation and support of many of today's stakeholders from the business, academic, government and non-profit communities. The success of next round of scientific and commercial research will be directly proportional to the degree of collaboration among the parties.

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