Hawaiʻi Natural Energy Institute Research Highlights

Alternative Fuels

Sustainable Aviation Fuel Production

OBJECTIVE AND SIGNIFICANCE: In 2019, commercial aviation in Hawaiʻi used nearly 700 million gallons of jet fuel, all of it is derived from petroleum. In 2023, as the state recovered from the combined effects of the pandemic and the Lāhainā wildfire, jet fuel consumption is approaching 2019 levels (Figures 1 and 2). The University of Hawaiʻi (UH) is a member of the Federal Aviation Administration's (FAA) Aviation Sustainability Center (ASCENT), a team of U.S. universities conducting research on production of sustainable aviation fuels (SAF). UH's specific objective is to conduct research that supports developments and decisions related to supply chains for alternative, renewable, sustainable, jet fuel production in Hawaiʻi. Results may inform similar efforts in other tropical regions.

BACKGROUND: This project was initiated in October 2015 and is now continuing into its 10th year. Activities undertaken in support of SAF supply chain analysis include:

- Conducting literature review of tropical biomass feedstocks and data relevant to their behavior in conversion systems for SAF production;
- Engaging stakeholders to identify and prioritize general SAF supply chain barriers (e.g. access to capital, land availability, etc.);
- Developing geographic information system (GIS) based technical production estimates of SAF in Hawaiʻi;
- Developing fundamental property data on biomass resources; and
- Developing and evaluating regional supply chain scenarios for SAF production in Hawaiʻi.

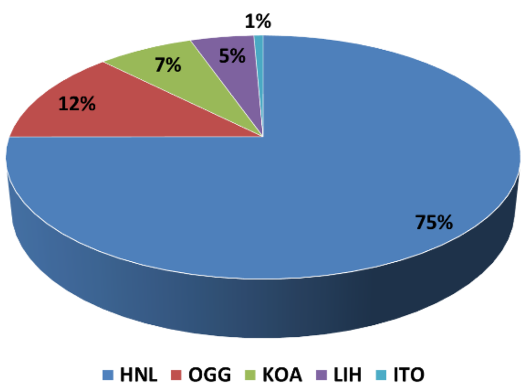

Figure 1. Commercial fuel use at Hawaiʻi's airports in 2023 totaled 638 million gallons (HNL, OGG, KOA, LIH, and ITO are Hawaiʻi's airports' codes).

PROJECT STATUS/RESULTS: Literature reviews of both biomass feedstocks and their behavior in SAF conversion processes have been completed and published. Based on stakeholder input, barriers to SAF value chain development in Hawaiʻi have been identified and reported. Technical estimates of land resources that can support agricultural and forestry-based production of SAF feedstocks have been completed using GIS analysis techniques. Samples from Honolulu's urban waste streams and candidate agricultural and forestry feedstocks have been collected and subjected to physicochemical property analyses to inform technology selection and design of SAF production facilities.

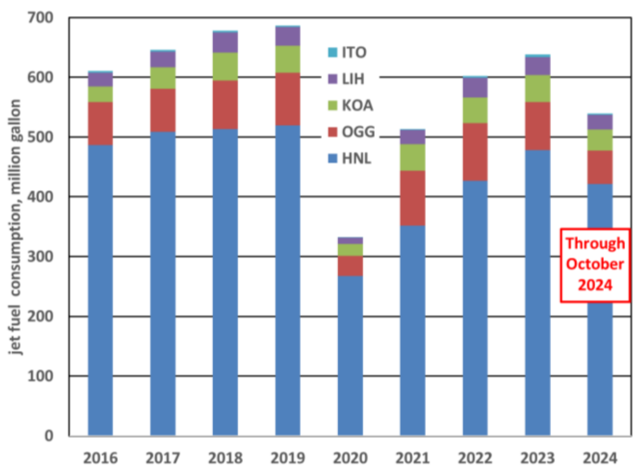

Figure 2. Commercial jet fuel consumption in Hawaiʻi.

Urban Waste: Fuel Properties of Oʻahu's Construction and Demolition Waste Streams

A sampling and analysis campaign was undertaken to characterize fuel properties of construction and demolition waste (CDW) streams on Oʻahu. Complete results were summarized and published in **Construction and Demolition Waste-Derived Feedstock: Fuel Characterization of a Potential Resource for Sustainable Aviation Fuels Production** in the *Frontiers in Energy Research* journal.

As shown in Figure 3, although the combustible fraction of the CDW samples have elevated ash levels compared to clean biomass materials, their heating values were comparable, indicating the presence of higher energy density materials. As with most refuse derived fuels, the amount of ash in the fuel and its composition is of particular importance – since ash impacts energy facility operations, maintenance, and emissions.

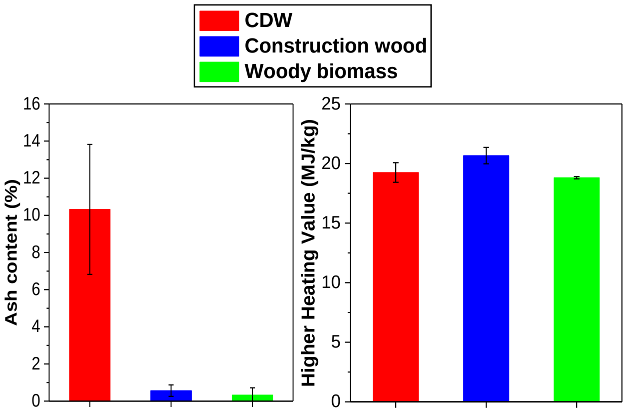

Figure 3. Ash content (left) and heating value (right) of the combustible fraction of CDW compared to construction wood and woody biomass.

Tests of clean wood fuel from the invasive species (Leuceana spp., common name koa haole) and synthetic CDW (sCDW) material were conducted at a commercial gasification technology provider facility to evaluate product composition and yields and identify contaminants (Figure 4). Test reports for koa haole ("***Gasification of Leucaena leucocephala stemwood***") and CDW ("***Gasification of synthetic CDW 1***"), respectively, are available on the HNEI website. The test results detail the reactor operating conditions, fuel characteristics, concentrations of major permanent gas species (H_2, CO, CH_4, CO_2), and concentrations of inorganic species present as contaminants in the product gas stream (H_2S, NH_3, HCl, As, Cd, Cr, Pb, Mg, P, K, Se, Na, Z, Hg). The increases of As, Pb, and Cr concentrations in the sCDW product gas compared to clean wood product gas were notable, in the case of arsenic increasing

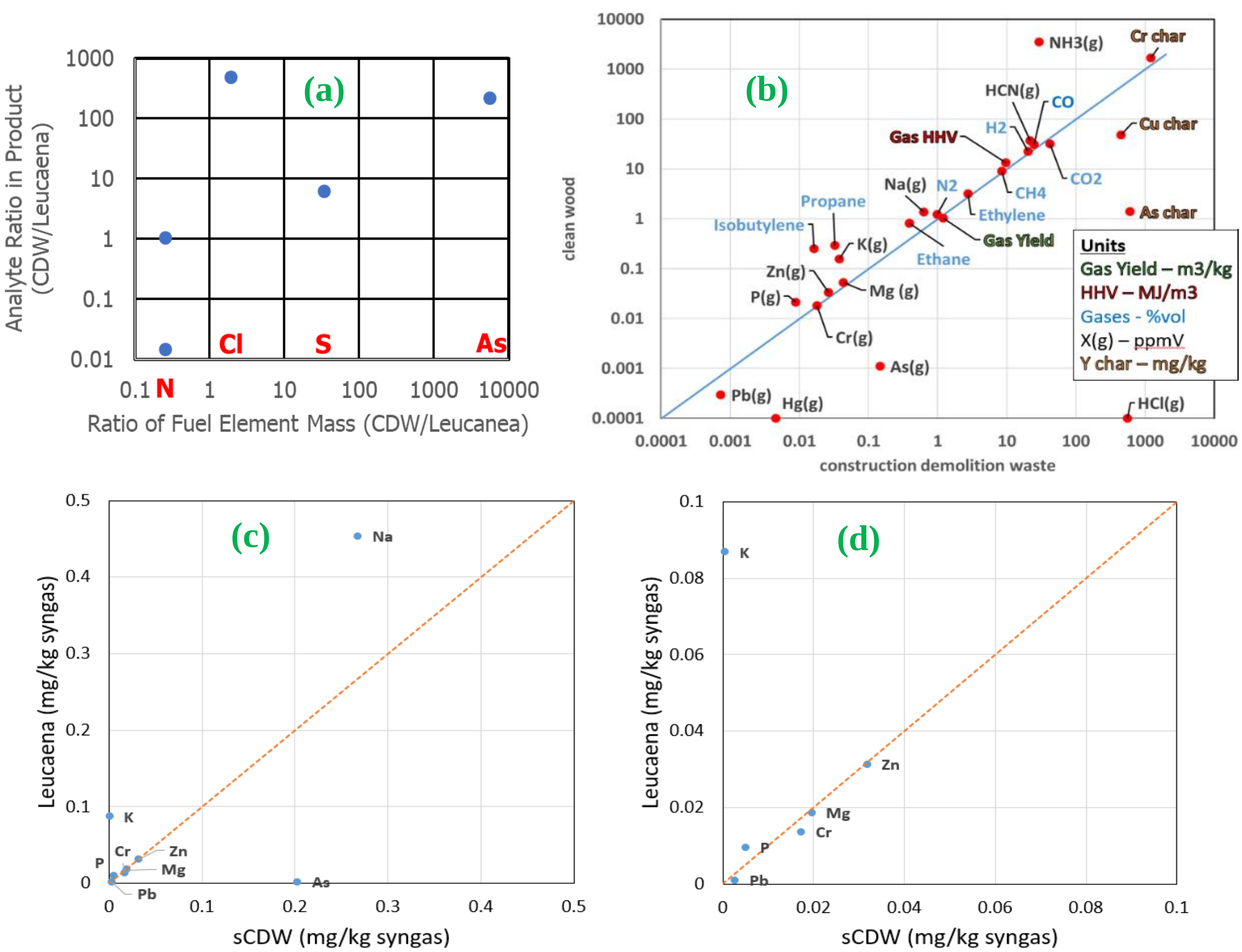

Figure 4. (a) Relative ratios of elements present in fuels to ratios in the product gas stream, (b) comparison of gasifier test measurements between clean fuel and CDW, (c) and (d).

from ~1 part per billion by volume (ppbv) to ~200 ppbv. Conversely, the clean wood fuel produces gas with elevated potassium (K) and sodium (Na) concentrations compared to the sCDW. The data indicate that managing the gas quality through feedstock treatment/blending or product gas cleanup will be required.

Urban Waste: Resource Logistics
Utilizing urban waste resources as feedstock for SAF production has the advantages of both reducing amounts of material entering the limited landfill space and reducing dependence on imported energy. A 2022 statewide assessment of urban waste resources entering landfills is summarized in Table 1[1].

Waste amounts generated by counties over the past nine years are plotted in Figure 5. Waste amounts generally scale according to population, with Honolulu having the largest total despite the use of waste for fuel in the HPOWER power plant. Integrating solid waste management and SAF production with a view of treating the state as a single management unit rather than four individual county units could be a beneficial approach to meet waste management, energy resiliency, and greenhouse gas abatement goals and improve economies of scale.

One approach for integrated solid waste management for SAF production would transport waste resources from neighbor islands and consolidate them with waste from the City & County of Honolulu (C&C) to fuel a gasification and Fischer-Tropsch (FT) conversion facility located on Oʻahu. Figure 6 shows a schematic of this approach. Urban waste generated on Oʻahu are transported to the SAF conversion facility by trucks via transfer stations. Waste generated in other counties are transported to ports by truck, transloaded to ocean transport, shipped to Oʻahu, transloaded to trucks, and finally transported

Table 1. Summary of combustible waste materials currently entering landfills (tons per year)[1].

County	Maui	Kauaʻi	Hawaiʻi	Honolulu	Total
Non-food biomass	111,151	43,279	120,346	22,207	296,983
Plastics and textiles	40,832	13,904	27,616	6,440	88,792
CDW	-	-	-	208,000	208,000
Urban Total	151,983	57,183	147,962	236,647	593,775

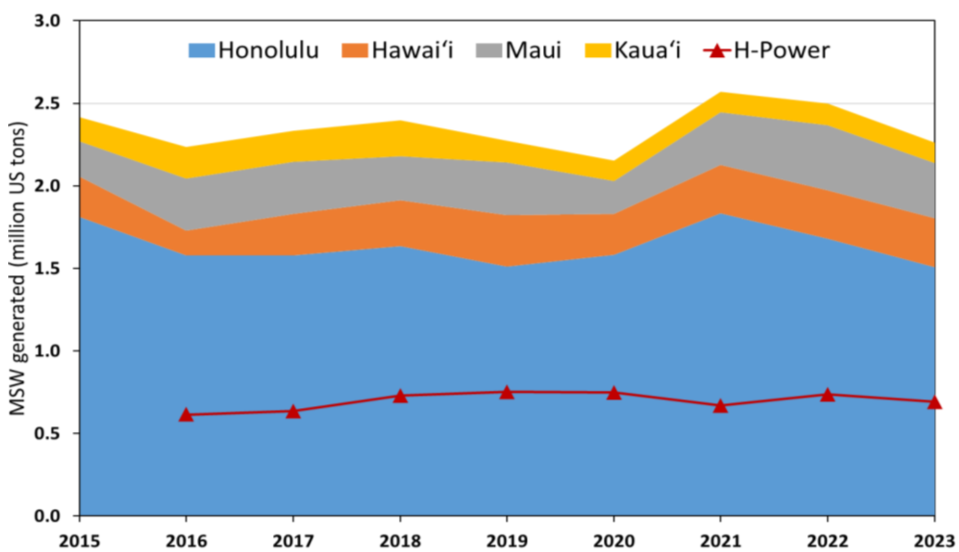

Figure 5. Annual MSW generation in Hawaiʻi by county. Data include recyclable and non-combustible materials which may not be used for SAF production.

[1] Adapted from Turn, S.Q., R.B. Williams, and W.Y. Chan. 2022. Resources for renewable natural gas production: A Hawaiʻi case study. *Environmental Progress & Sustainable Energy*. e14002. https://doi.org/10.1002/ep.14002.

to the SAF production facility. SAF is delivered by trucks to Daniel K. Inouye International Airport (HNL). Six different scenarios of non-recycled urban waste utilization for SAF production are listed in Table 2. Differences between them result from assumptions on the use of food waste and mixed plastics and the fraction of waste diverted to the HPOWER waste to energy plant currently operated in C&C. Food waste is typically a high moisture fraction of the waste stream and can be diverted for animal feed or as feedstock for anaerobic digestion. Plastics are typically the largest source of non-biogenic carbon present in waste. The remaining categories – paper, yard trimmings, combustible C&D material, mixed organics, and mixed MSW – are all included in each of the waste scenarios. All categories can be commonly identified from data included in integrated solid waste management plans prepared by individual counties.

Estimates of production potential from the six waste utilization scenarios are shown in Figure 7. Scenarios 1, 3, and 5 that don't include HPOWER operation yield the highest SAF production values ranging from 38 to 45 million gallons annually. Diverting food waste and plastics from the material fueling the SAF process accounts for the difference of 7 million gallons per year. Comparing SAF production potential under Scenarios 3 (44 million gal/yr) and 4 (21 million gal/yr) demonstrates the impact of operating HPOWER while diverting food waste but including plastic (non-biogenic carbon). Scenario 6 has the lowest SAF production potential, 18 million gal/yr, the result of diverting waste to HPOWER and excluding both food waste and plastics.

Figure 8 summarizes preliminary assessment of life cycle greenhouse gas emissions per MJ for each of the six scenarios. The results show that the estimated emissions range from 32-53 gCO_2e/MJ. As reference, petroleum jet fuel has a GHG intensity value of 90 g CO_2e/MJ. Continued operation of HPOWER reduces the amount of MSW available on Oʻahu for SAF production, increasing the relative weight of MSW

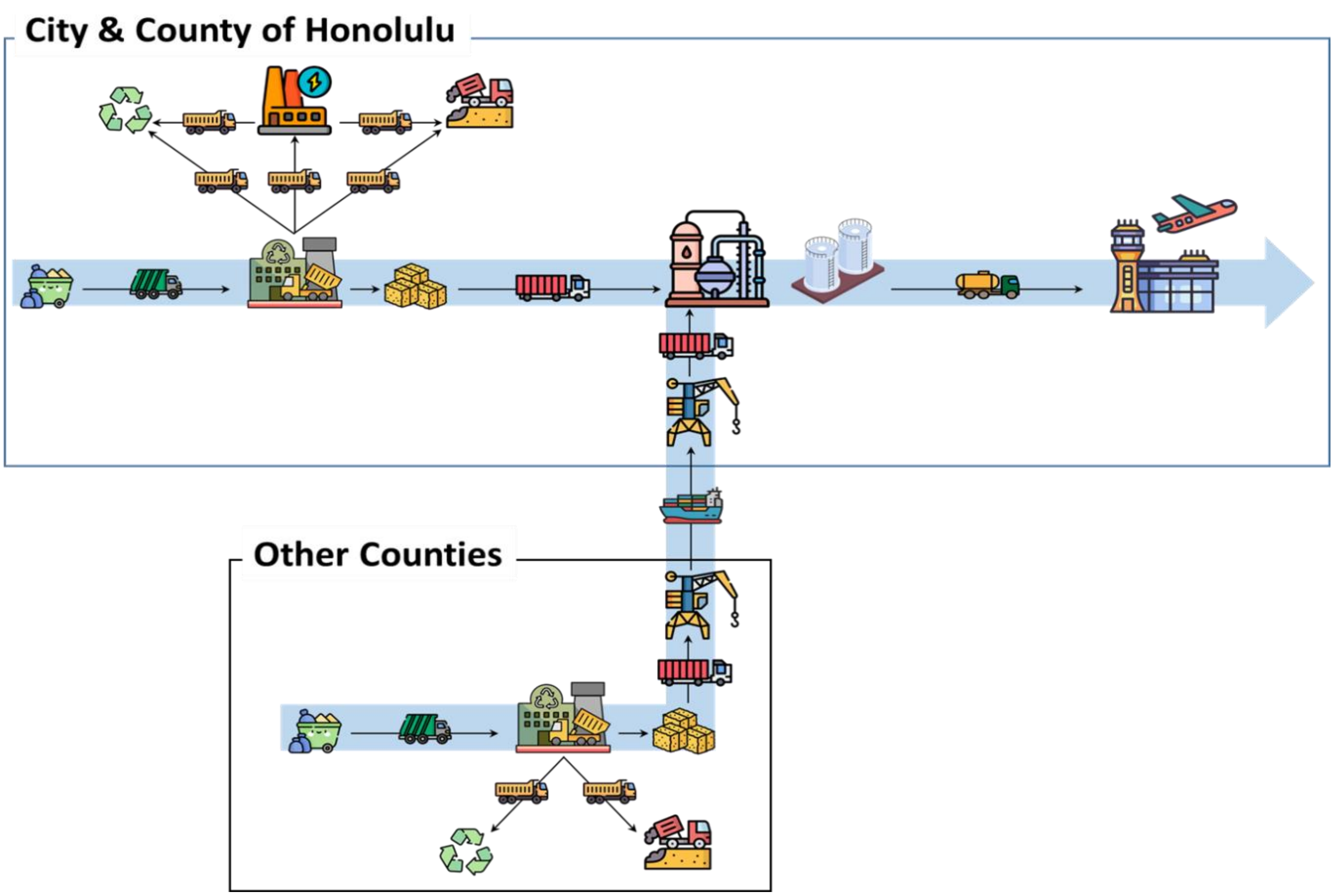

Figure 6. Schematic of waste management across the state in support of SAF production on Oʻahu.

transported from outer islands and their associated GHG intensities (GHG_e per MJ) – compare Scenarios 1 and 2. Scenarios 3 and 4 consider the impact of removing food waste from the MSW feedstock coupled with HPOWER operations. Food waste is a high moisture component of MSW and may be diverted because it is a commonly used feedstock for anaerobic digestion applications and can also be used as animal feed. Food waste removal produces a small net increase in GHG emission intensity resulting from the higher percentage of non-biogenic material in the waste stream. Scenarios 5 and 6 consider removal of plastics from the feedstock stream. Although it reduces the SAF production volumes (as shown in Figure 7), it results in a much lower GHG value since plastics contain non-biogenic carbon.

Table 2. Solid waste utilization scenario assumptions for SAF production and HPOWER (Yes indicates that waste category is included or HPOWER is operated; No indicates that waste category is excluded or HPOWER is not operated.)

Scenario	1	2	3	4	5	6
HPOWER	No	Yes	No	Yes	No	Yes
Food Waste	Yes	Yes	No	No	No	No
Mixed Plastics	Yes	Yes	Yes	Yes	No	No
Combustible C&D Materials	Yes	Yes	Yes	Yes	Yes	Yes
Mixed Organics	Yes	Yes	Yes	Yes	Yes	Yes
Mixed MSW	Yes	Yes	Yes	Yes	Yes	Yes
Yard Trimmings	Yes	Yes	Yes	Yes	Yes	Yes
Paper	Yes	Yes	Yes	Yes	Yes	Yes

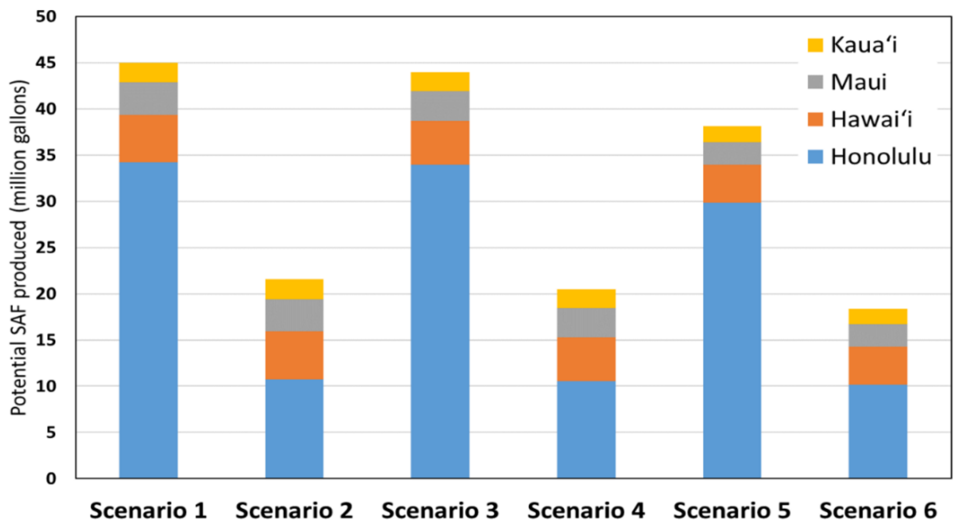

Figure 7. Technical SAF potential from combustible urban waste for six utilization scenarios.

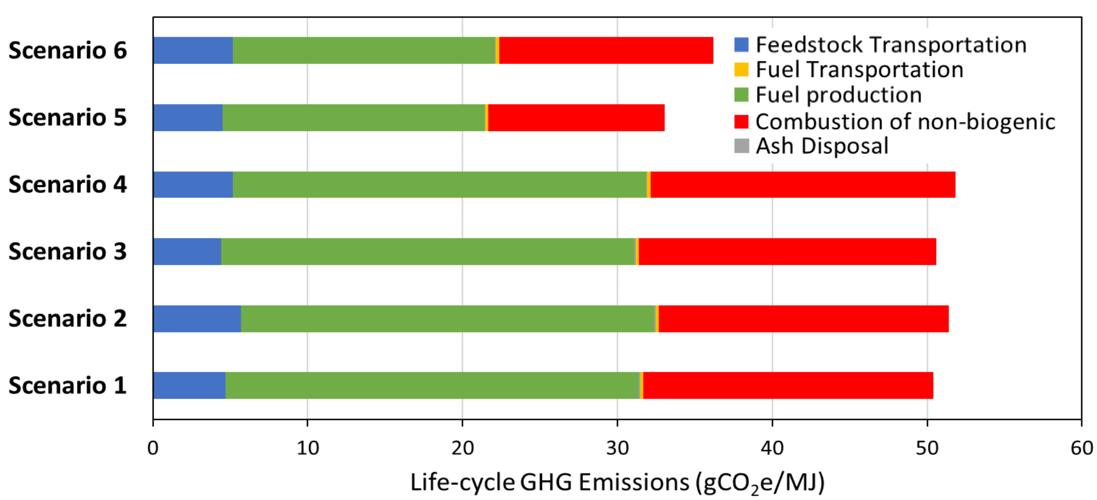

Figure 8. Estimation of GHG emissions from six waste utilization scenarios that include SAF production and combustion in HPOWER.

Biomass: Exploration of Hawai'i Feedstocks

Figure 9 compares land use in 1937, 1980, 2015, and 2020 for the nearly 2 million acres of agricultural lands in Hawaiʻi[2]. Bringing agricultural lands back into production can support diversification of the economy and support rural development. Biomass feedstocks for sustainable aviation fuel production are options that can contribute to this revitalization. This work was summarized and published in **Review of Biomass Resources and Conversion Technologies for Alternative Jet Fuel Production in Hawaiʻi and Tropical Regions** in the *Energy and Fuels* journal.

The EcoCrop model was used to complete an assessment of plant production requirements to agro-ecological attributes of agricultural lands in the State. Land use constraints included agricultural zoning, land capability classes (an indicator of soil quality), slope, service by irrigation systems, and current agricultural activities. The analysis focused on sites capable of rain-fed production to avoid using irrigated lands that could support food production. Oil seed crops, woody crops, and herbaceous crops were all considered; an example is shown for a eucalyptus species (Figure 10).

The EcoCrop model provides an estimate of each energy crops' productivity across the agricultural landscape. Aggregated yield of biobased feedstock and conversion efficiency from feedstock to final energy product were used as the basis for SAF technical potential estimates under four scenarios:

- Scenario 1 - agricultural zoning, slope less than 20%, land capability class 1 to 6
- Scenario 2 - agricultural zoning, slope less than 20%, land capability class 1 to 6, excluding land serviced by irrigation systems,
- Scenario 3 - agricultural zoning, slope less than 20%, land capability class 1 to 6, excluding land serviced by irrigation systems and land currently in agricultural use, and
- Scenario 4 - agricultural zoning, slope less than 20%, land capability class 1 to 6, excluding land serviced by irrigation systems and land currently in agricultural use other than pasture.

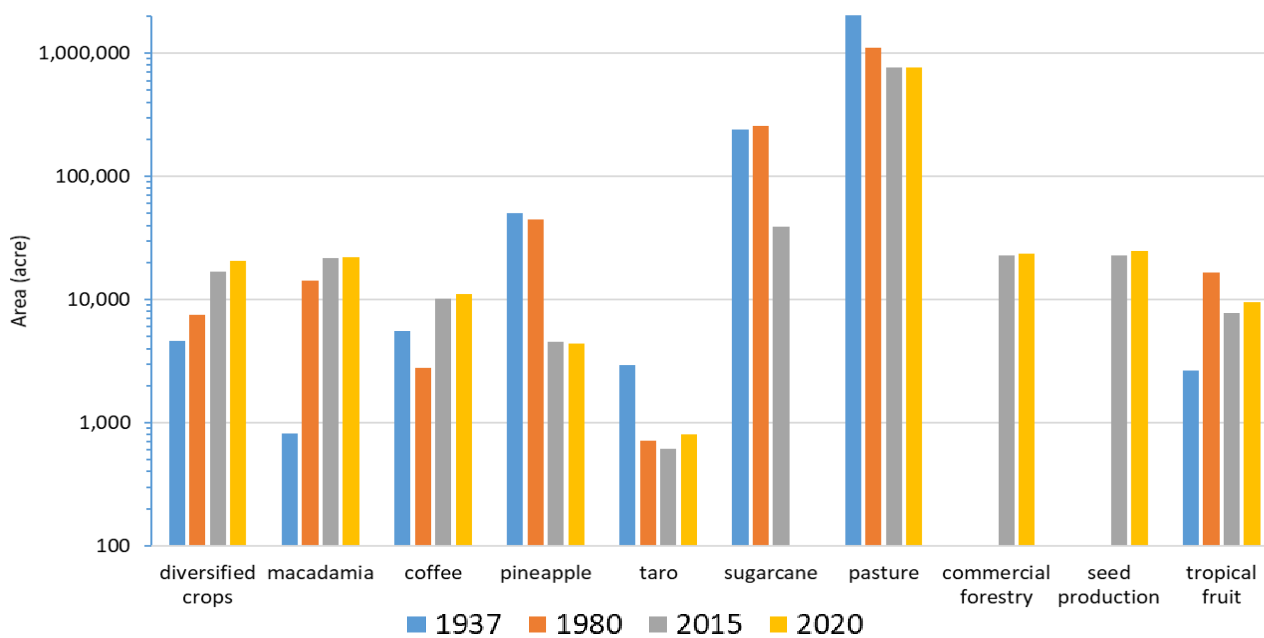

Figure 9. Hawaiʻi agricultural land use patterns, 1937 to 2020[2].

[2] Adapted from data in a) Melrose, J., R. Perroy, S. Cares. 2015. *Statewide agricultural land use baseline 2015*. University of Hawaiʻi at Hilo. Prepared for the Hawaiʻi Department of Agriculture. Honolulu, Hawaiʻi and b) Perroy, R. and E. Collier. 2024. *2020 Update to the Hawaiʻi statewide agricultural land use baseline*. University of Hawaiʻi at Hilo. Prepared for the Hawaiʻi Department of Agriculture. Honolulu, Hawaiʻi.

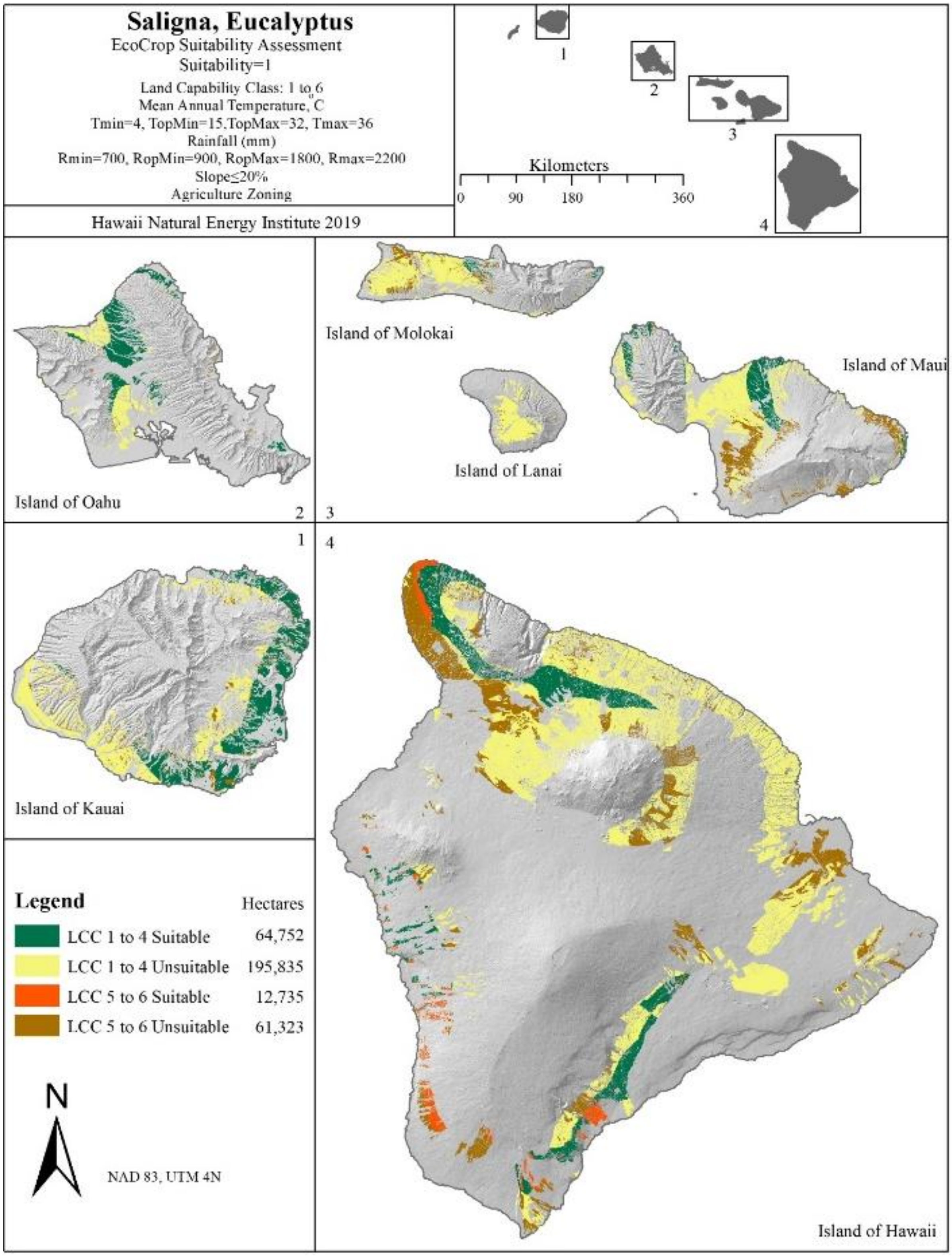

Figure 10. EcoCrop assessment of Saligna, Eucalyptus.

All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions. Results of the analyses are shown in Figure 11. Note that the results are not mutually exclusive, i.e. the same land area may be included in the estimates of multiple crops. Scenario 1 includes the greatest land area and this is reflected in highest annual SAF production potential estimates, of up to ~100 million gallons. Scenario 2 removes any land serviced by an irrigation system from the analyses, resulting in a reduction in potential to a ~80 million gallons.

Scenario 3 further restricts available lands by excluding those under production identified in a study conducted by the University of Hawai'i at Hilo (UH Hilo) for the Hawai'i Department of Agriculture[3], resulting in SAF production potential estimates <40 million gallons per year. Scenario 4 considers the dual use of land to support energy crops and pasture by including pasture lands identified in the UH Hilo Baseline report. This results in maximum estimates of ~70 million gallons per year. A report detailing these results is currently being drafted.

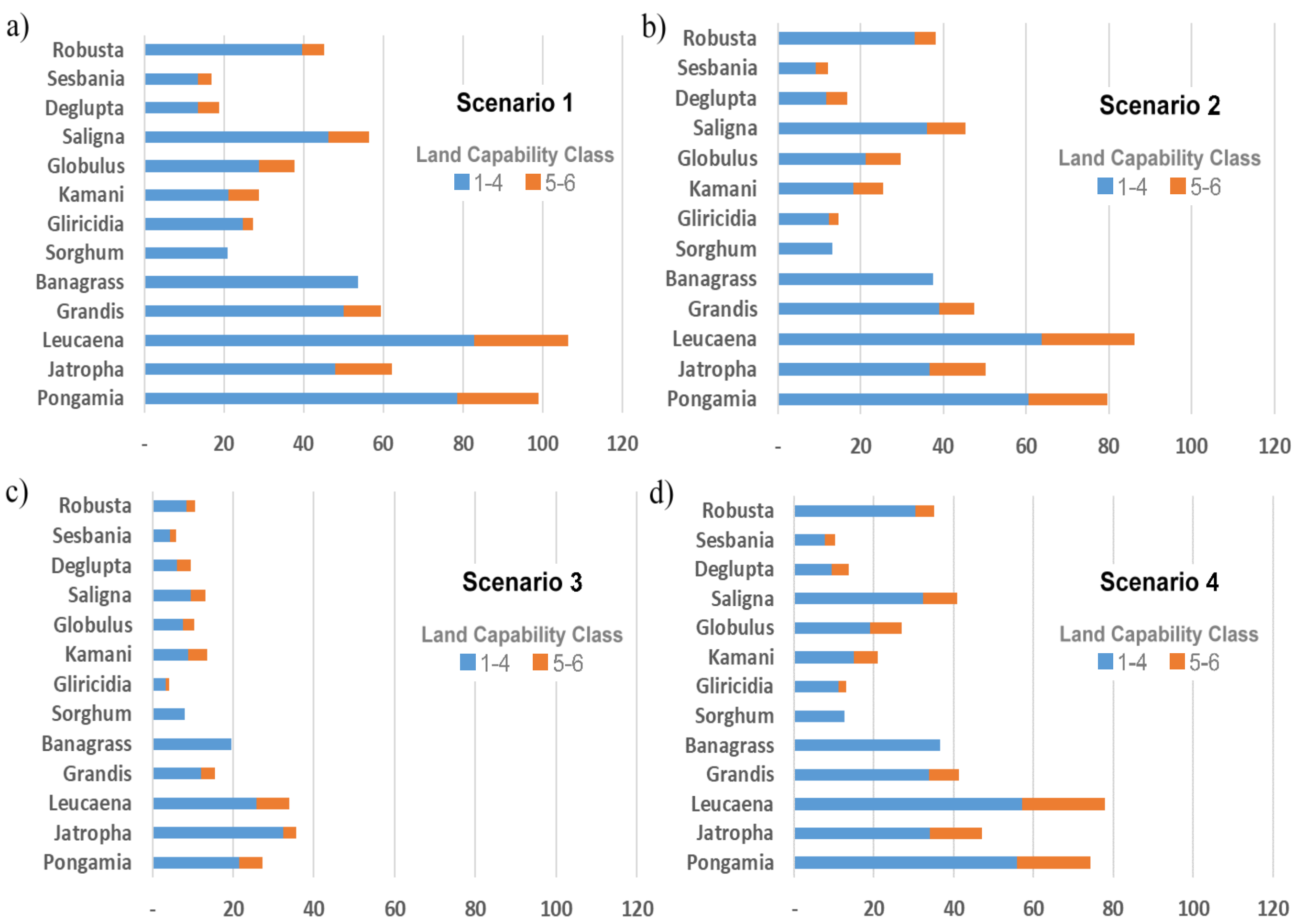

Figure 11. SAF potential (million gallons per year) for 13 energy crop feedstocks under four scenarios: (a) agricultural zoning, slope less than 20%, (b) agricultural zoning, slope less than 20%, excluding land serviced by irrigation systems, (c) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems and land currently in agricultural use, and (d) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems and land currently in agricultural use other than pasture. All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions.

[3] Melrose, J., R. Perroy, S. Cares. 2015. *Statewide agricultural land use baseline 2015*. Prepared for the Hawai'i Department of Agriculture. Honolulu, Hawai'i.

Biomass: Pongamia Logistics

EcoCrop energy crop modeling identified pongamia as having the greatest oil production potential based on suitable growing area and yield. The geographic distribution of suitable growing areas across the state provides an opportunity to select pongamia primary processing sites that minimize transportation costs. Seeds in their pods would be harvested and transported to a primary processing location where the seed and pod could be separated – oil could be extracted from the seed, and oil and de-oiled seed cake could be upgraded. Land zoned for industrial use (brownfield site) on each island was considered as potential primary processing sites. Greenfield sites were also considered – identified as land zoned for agriculture with slope less than 5%, and a minimum contigous area of 125 acres. This would accomodate space needed for processing, storage, and possible colocation of complementary industries utilizing the de-oiled seedcake and pod to develop coproducts. A tonne-kilometer value, Tkm_i, was calculated for all i candidate processing locations using Equation 1.

$$Tkm_i = \sum_{j=1}^{n} m_j \cdot d_j \qquad \text{(Eq. 1)}$$

Where m_j is the mass of seed pod harvested at a production location j, d_j is the distance traveled over the existing road network between production location j to the candidate processing site i, and n is the number of pongamia production locations. Production locations were based on analysis using a 1 km x 1 km grid. A relative index, C_{ik}, shown in Equation 2, was used to compare *Tkm* values across islands.

$$C_{ik} = \left(\frac{Tkm_i - Tkm_{min}}{Tkm_{max} - Tkm_{min}}\right)_k \qquad \text{(Eq. 2)}$$

Where Tkm_{min} and Tkm_{max} are the minimum and maximum *Tkm* values, respectively, for island k. Candidate sites for Scenario 1, ranked from lowest (C_{ik}=0) to highest (C_{ik}=1) value, are shown in Figures 12 and 13 for brownfield and greenfield locations, respectively.

Figure 14 identifies processing site locations that would minimize transportation requirements for harvested pongamia seed-in-pod from Scenario 4 under constraints of maximum transport distances: 77 km (brown and green), 90 km (pink and tan), and 110 km (blue). As the permissible transportation distance decreases, optimum locations shift from Waimea and Pahala (110 km) to Waimea and Nāʻālehu (90 km), to Kawaihae and Nāʻālehu (77 km). The total *Tkm* value for the two processing site locations are 38.6, 36.2, and 45.0 million ton·km for the 110, 90, and 77 km constraints, respectively, with a marginal concomitant reduction in total amounts of seed-in-pod transported, 1.5 million ton per year. Note that lines in Figure 14 indicate the association between production area (dot) and processing site (star), but the transport distances are based on road network values.

Figure 15 identifies processing sites selected using the same travel distance limits (77, 90, and 110 km) but with an added constraint limiting facility processing capacity to 750,000 tons per year at any given location. Decreasing travel distance limits shifts the locations of the sites that minimize transportation costs. This evaluation would be useful to repeat to site facilities with smaller processing capacities as the first orchards are planted and the total crop harvest is limited.

Greenfield site options are more numerous than brownfield locations and may afford reductions in transportation requirements as shown in the figures. Brownfield sites are anticipated to offer access to pre-existing utilities that could reduce costs of developing the processing facilities. The locations for minimum cost sites depend on the production scenarios for pongamia. Pongamia production system planning would require verification of industrial zoning, farmer acceptance of pongamia production, community acceptance, and economic viability of all value chain participants. Continued system evaluation is planned moving forward.

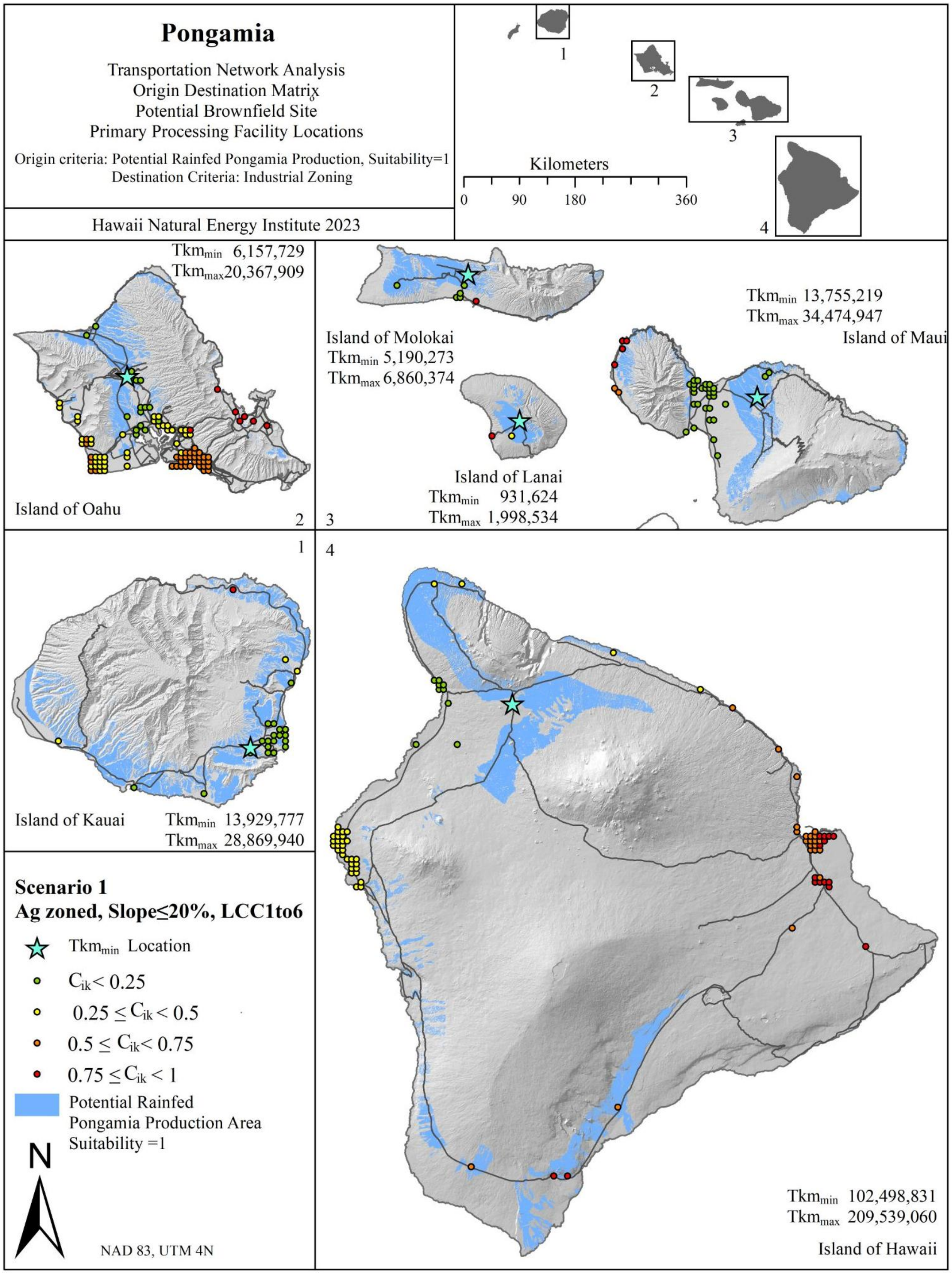

Figure 12. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central brownfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability values of 1.0 for pongamia under rainfed conditions. Potential brownfield processing locations, shown as colored circles, are zoned for industrial use. The star on each island identifies the location of Tkm_{min} corresponding to $C_{ik} = 0$.

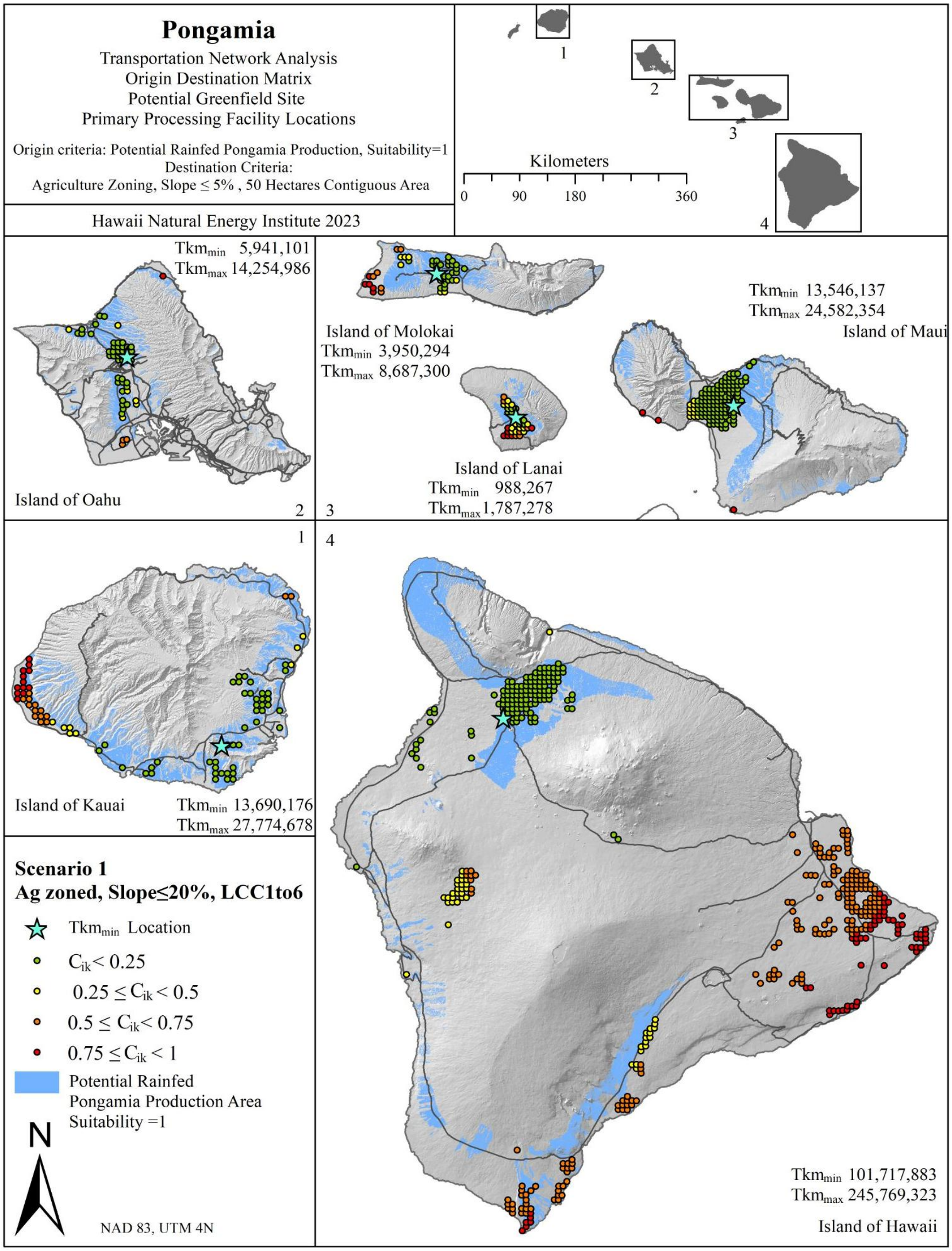

Figure 13. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central greenfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability values of 1.0 for pongamia under rainfed conditions. Potential greenfield processing locations, shown as colored circles, are zoned for agriculture, have slopes ≤5%, and have 125 acres (50 hectares) of contiguous area. The star on each island identifies the location of Tkm_{min} corresponding to $C_{ik} = 0$.

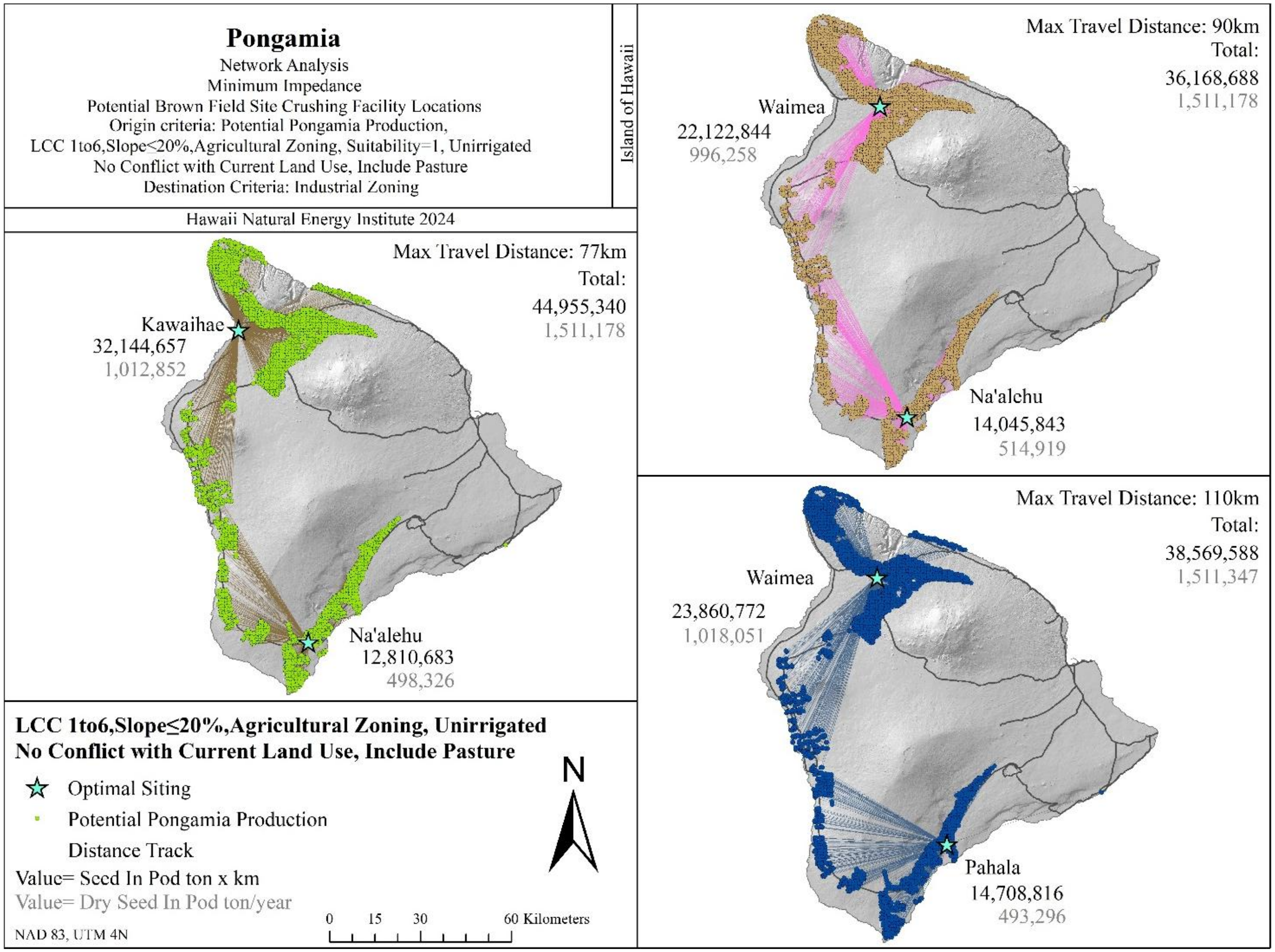

Figure 14. Brownfield processing site locations that would minimize transportation requirements for harvested pongamia seed-in-pod from Scenario 4 under constraints of maximum transport distances: 77 km (brown and green), 90 km (pink and tan), and 110 km (blue). Note that lines indicate the association between production area (dot) and processing site (star), but the transport distances are based on road network values.

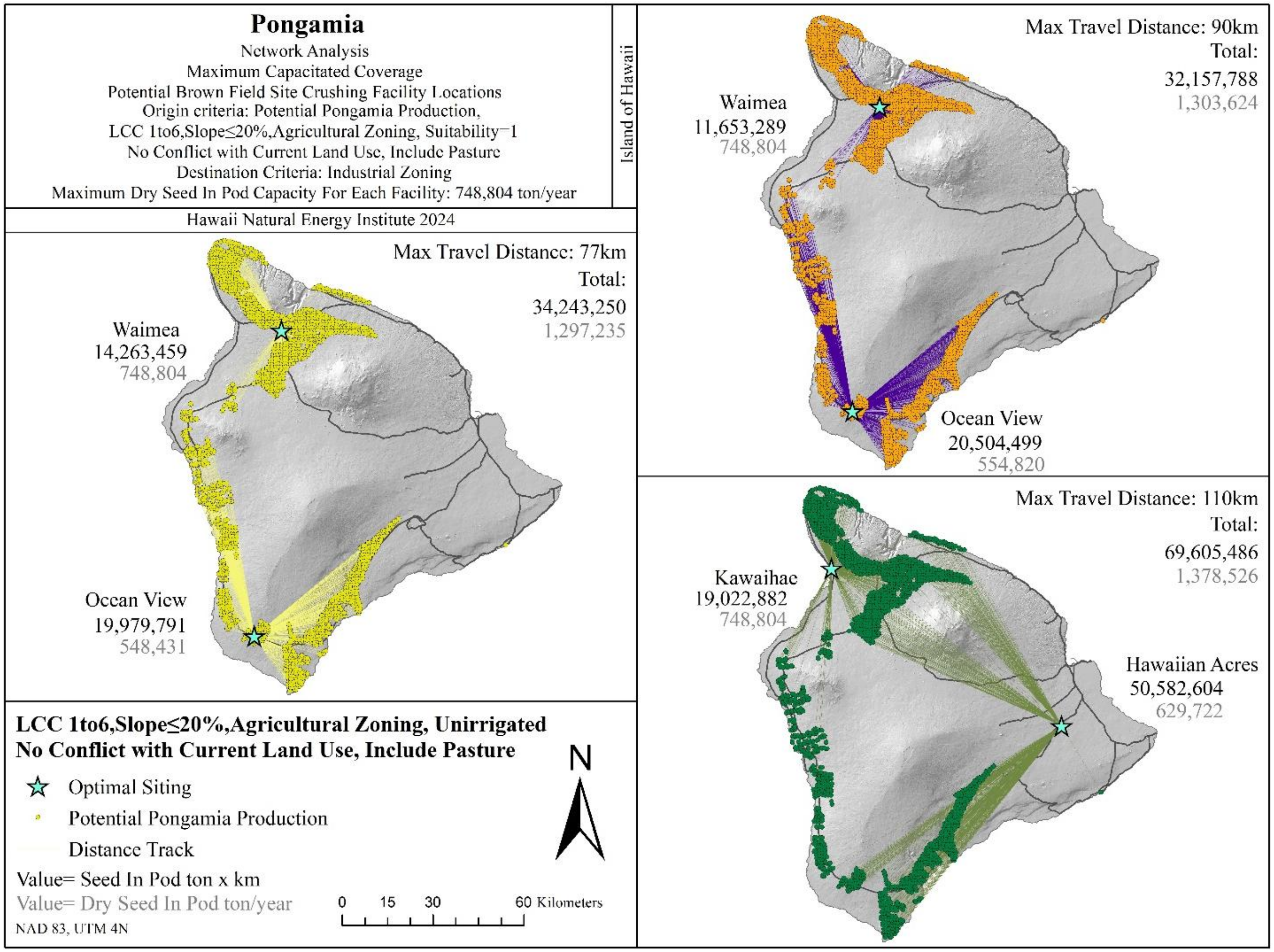

Figure 15. Brownfield processing site locations that would minimize transportation requirements for harvested pongamia seed-in-pod from Scenario 4 under constraints of processing facility capacity <750,000 tons per year and maximum transport distances: 77 km (yellow), 90 km (purple and orange), and 110 km (green). Note that lines indicate the association between production area (dot) and processing site (star), but the transport distances are based on road network values.

Biomass: Evaluation of Pongamia

Of the sustainable aviation fuels currently approved by ASTM and the FAA, those based on the use of oils derived from plants and animals have the highest SAF yield and the lowest production costs. Pongamia (*Millettia pinnata*) (Figure 16) is a tree, native to the tropics, that bears an oil seed and has plantings established on Oʻahu, Maui, and Hawaiʻi island. Pongamia is largely sourced from wild collection in many parts of the world. Pongamia production, processing, and use as an agricultural crop for SAF production would require a value chain (Figure 17). Several projects have been undertaken to provide information needed to develop this value chain. Results are summarized below.

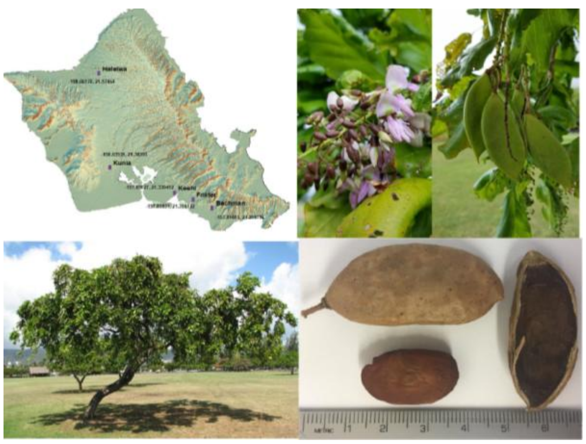

Figure 16. Locations and images of Pongamia.

Economics of Producing Pongamia in Hawaiʻi

Figure 18 proposes common agricultural activities for orchard production of pongamia and illustrates material and energy flows crossing the orchard boundary. Outputs from the orchard include harvested pongamia seed in pod, pongamia trees when the orchard is removed, and land, air, and water emissions. Figure 19 provides additional detail. Growing pongamia trees in Hawaiʻi will require extensive land preparation. In the case of land that has been out of production for several years, preparation may include removal of pre-existing trees, weeds, and debris. Once the soil is prepared, young trees will be purchased and planted. Additional costs may include royalties and grafting costs if specialized cultivars are used. Once the young trees are in the ground, they will need to be pruned, irrigated, and fertilized, and protected from insects and weeds. These cultural costs are higher initially and then decline as the trees mature. When the trees begin producing seed pods, the cost of harvesting will be incurred.

Production costs are evaluated over a 25-year time period. In the first year, the land is prepared at a cost of $265 per acre, then trees are planted at a cost of $3,848 per acre. The newly planted trees are irrigated, pruned, fertilized, and treated for weeds (through mowing and herbicide use) at an initial cost of $600 per acre per year in year 1, rising to $852 per acre in

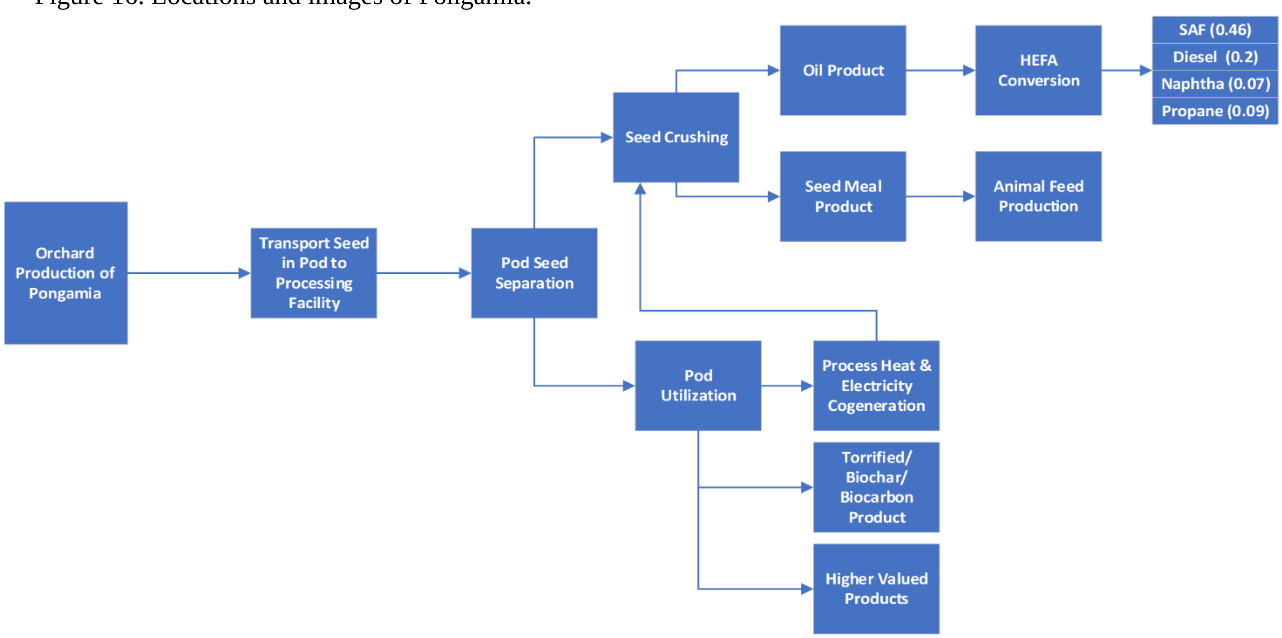

Figure 17. Pongamia value chain from orchard production, aggregation at a processing facility, oil separation, HEFA conversion, and upgrading of byproduct seed meal and fibrous pods.

year 2, $1,014 per acre in year 3, falling to $277 per acre in year 4 and continues to decline gradually reaching $249 by year 25. In year 3, the trees begin flowering and producing seedpods which will be harvested and sold. Initial yields are 0.36 Mg seed (hulled) per acre, peak yields are 3.64 Mg seed (hulled) per acre. Seed yield peaks in year 18 and declines annually through year 25. Baseline production assumptions are displayed in Table 3. Annual seed production is illustrated in Figure 20.

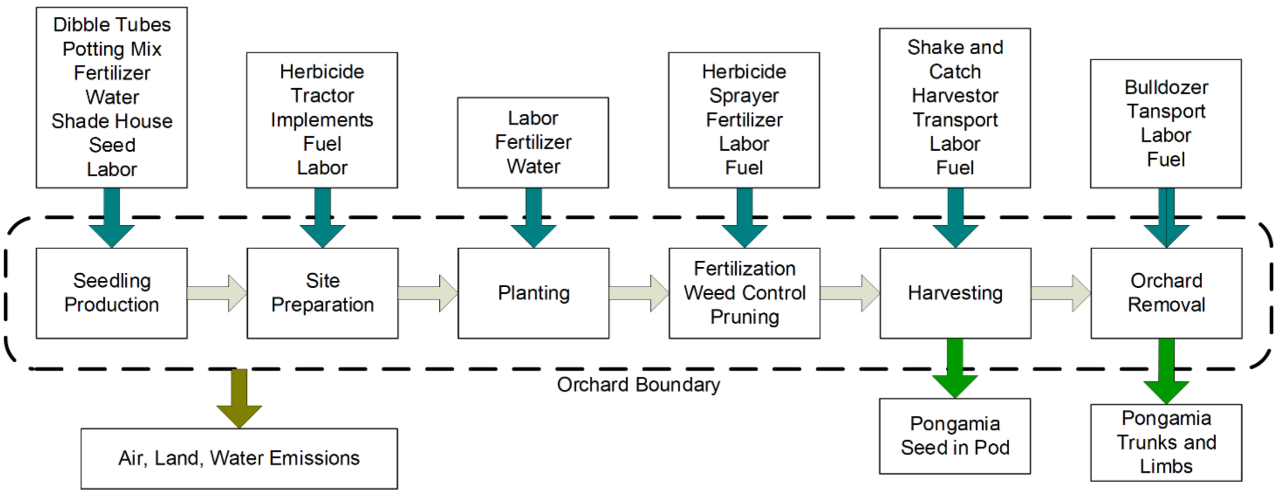

Figure 18. Common agricultural activities propsed for orchard production of pongamia and material and energy flows crossing the orchard boundary.

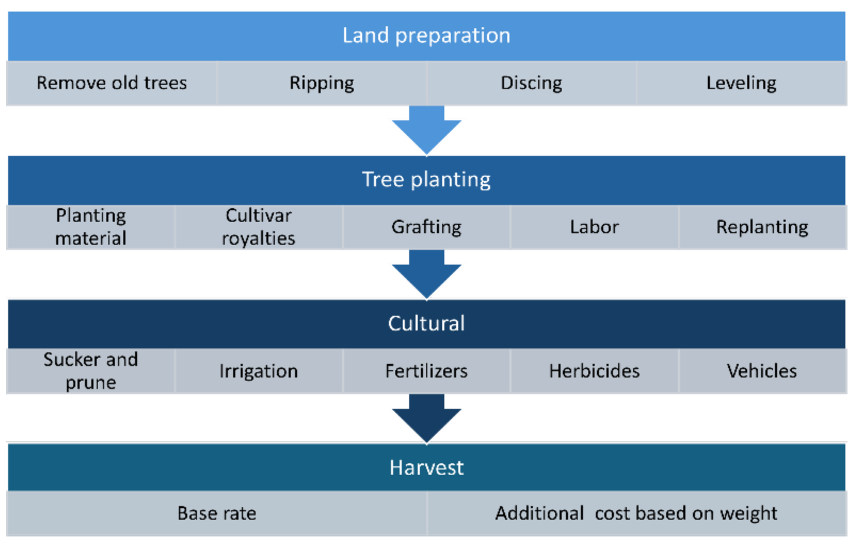

Figure 19. Factors of production proposed for pongamia production systems.

Table 3. Baseline cost assumptions.

Item	Year	Units	Baseline	
Land preparation cost	1	$ per ac	$265	
Tree planting cost	1	$ per ac	$3,848	
			Low	High
Cultural costs (range)	1 to 25	$ per ac	$249	$1,014
Harvest costs (range)	3 to 25	$ per ac	$162	$527
Yield range	3 to 25	Mg seed per ac	0.36	3.64

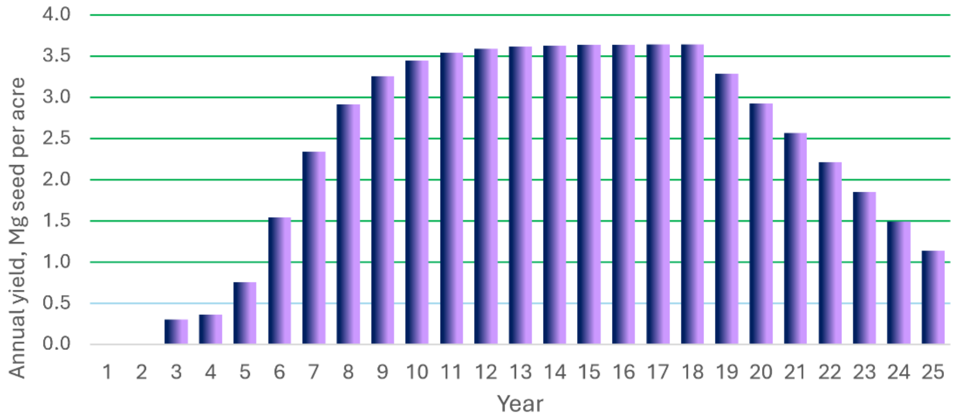

Figure 20. Pongamia seed yield over time in Mg hulled seed per acre per year.

For a one-acre plot of land, results indicate the net revenues will be negative for the first four years of production. In year 5, revenues from the sale of Pongamia seed pods will exceed culture and harvest costs and results in positive net revenues through year 25. With a seed price of $597 per Mg hulled seed, net revenues over 25 years will total $10,522 per acre, not discounted.

Biomass: Pongamia Fuel Properties
Pongamia is a potential resource for renewable fuels in general and sustainable aviation fuel in particular. The physicochemical properties of reproductive material (seeds and pods) from pongamia trees grown in different environments at five locations on O‘ahu were characterized (Figure 21). Proximate and ultimate analyses, heating value, and elemental composition of the seeds, pods, and de-oiled seed cake were determined. The oil content of the seeds and the properties of the oil were determined using American Society for Testing and Materials (ASTM) and American Oil Chemist’s Society (AOCS) methods. The seed oil content ranged from 19 to 33% wt. across the trees and locations. Oleic (C18:1) was the fatty acid present in greatest abundance (47 to 60% wt) and unsaturated fatty acids accounted for 77 to 83% wt of the oil. Pongamia oil was found to have similar characteristics as other plant seed oils (canola and jatropha) and would be expected to be well suited for hydro-processed production of sustainable aviation fuel. These results were published in **Fuel Properties of Pongamia (*Millettia pinnata*) Seeds and Pods Grown in Hawai‘i** in the *ACS Omega* journal.

Figure 21. Pathways from Pongamia seed pods to fuel.

Biomass: Pongamia Coproduct Development
Additional studies were devoted to developing coproducts from pongamia pods. Leaching and torrefaction experiments were performed to remove inorganic constituents and reduce the oxygen content of the pods (Figure 22). A 2^3 factorial design of the leaching treatment determined the impacts of process operating parameters (i.e. rinse water temperature, rinse duration, and particle size) on the composition and physicochemical properties of the pods and the water. The higher heating value of the pods was found to increase from 16 to 18-19 MJ/kg after leaching, while the ash content was reduced from 6.5% to as low as 2.8% wt, with significant removal of sulfur (S), chlorine (Cl), and potassium (K). The chemical oxygen demand, non-purgeable organic carbon, and total nitrogen of the post-experiment leachates were all found to increase with the rinse water temperature and rinse duration but decrease with the increase of particle size. Leached pods were further processed via torrefaction and the targeted mass and energy yields,

~70% and 85%, respectively, were reached at a process temperature of 270°C. The S, Cl, and K contents of the leached, torrefied pods were found to be lower than that of the raw pods. The reuse of leachate on successive batches of fresh pods showed that ash removal efficiency was reduced after three cycles, although some removal was possible through 15 cycles.

Pongamia pod leaching processes and pod torrefaction processes were summarized and published in **Water leaching for improving fuel properties of pongamia Pod: Informing process design** and **Upgraded pongamia pod via torrefaction for the production of bioenergy**, both in the journal *Fuel*, respectively.

Figure 22. Laboratory scale leaching and torrefaction test equipment.

Biomass: Pongamia Invasiveness Assessment
Pongamia (*Millettia pinnata*) is a tree, native to the tropics, which bears an oil seed and has plantings established on O‘ahu. Under this project, an observational field assessment of trees in seven locations on O‘ahu was conducted by Professor Curtis Daehler (UH Dept. of Botany) to look for direct evidence of pongamia escaping from plantings and becoming an invasive weed. Although some pongamia seedlings were found in the vicinity of some pongamia plantings, particularly in wetter, partly shaded environments, almost all observed seedlings were restricted to areas directly beneath the canopy of mother trees. This finding suggests a lack of effective seed dispersal away from pongamia plantings. Based on its current behavior in the field, pongamia is not invasive or established outside of cultivation on O‘ahu. Because of its limited seed dispersal and low rates of seedling establishment beyond the canopy, the risk of pongamia becoming invasive can be mitigated through monitoring and targeted control of any rare escapes in the vicinity of plantings. Seeds and seed pods are water dispersed, so future risks of pongamia escape and unwanted spread would be minimized by avoiding planting at sites near flowing water, near areas exposed to tides, or on or near steep slopes. Vegetative spread by root suckers was not observed around plantings on O‘ahu, but based on reports from elsewhere, monitoring for vegetative spread around plantations is recommended; unwanted vegetative spread might become a concern in the future that could be addressed with localized mechanical or chemical control. A detailed technical report titled "***Observational Field Assessment of Invasiveness of Pongamia (Millettia pinnata), A Candidate Biofuel Crop in Hawai‘i***" summarized this work and is available on HNEI's website.

Biomass: Other Feedstocks
Other potential feedstocks for Hawai‘i, kukui (*Aleurites moluccanus*) and kamani (*Calophyllum inophyllum*) nut oils, were also explored. The oil content of the kukui nuts is ~60% wt, which is ~20-30% wt higher than that of pongamia seeds and kamani nuts. The unsaturated fatty acids, however, accounted for ~90 % wt of the kukui nut oil, slightly higher than that of kamani nut (~75% wt) and pongamia seed oil. Kukui and kamani nut oil are different from the pongamia seed oil, in that the primary fatty acid is linoleic acid (C18:2). The results of the study conducted on kukui were published in **Comprehensive Characterization of Kukui Nuts as Feedstock for Energy Production in Hawai‘i** in the *ACS Omega* journal.

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