Hawaiʻi Natural Energy Institute Research Highlights

Alternative Fuels

Sustainable Aviation Fuel Production

OBJECTIVE AND SIGNIFICANCE: Commercial aviation in Hawaiʻi currently uses nearly 700 million gallons of jet fuel per year, all of it is derived from petroleum. The University of Hawaiʻi (UH) is a member of the Federal Aviation Administration's (FAA) Aviation Sustainability Center (ASCENT) team of U.S. universities conducting research on production of sustainable aviation fuels (SAF). UH's specific objective is to conduct research that supports development of 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 9th 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.

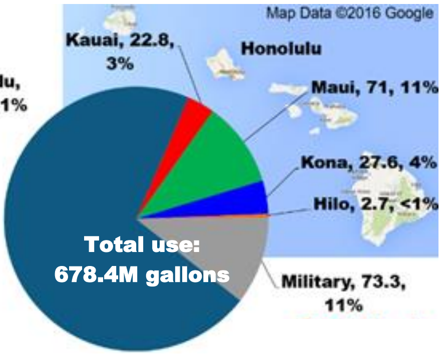

Figure 1. Commercial and military jet fuel use in 2015.

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.

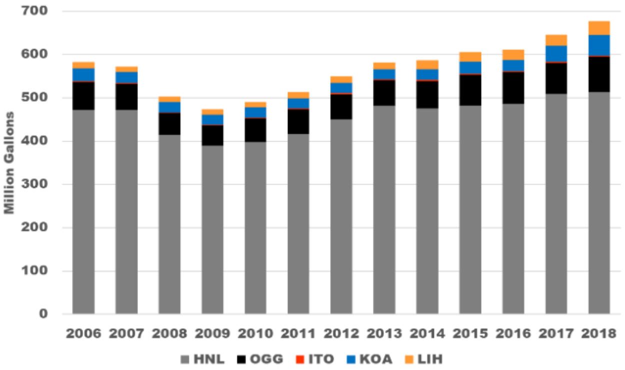

Figure 2. Commercial jet fuel consumption in Hawaiʻi.

Fuel Properties of 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 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.

Tests of clean wood fuel from the invasive species (Leuceana spp., common name koa haole) and CDW 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 HNEI’s 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 CDW product gas compared to clean wood product gas were notable, in the case of arsenic increasing from ~1 part per billion (ppb) to ~200 ppb. The data indicate that managing the gas quality through feedstock treatment/blending or product gas cleanup will be required.

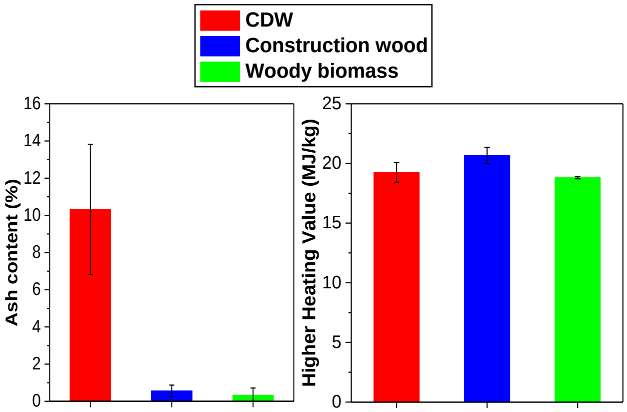

Figure 3. Ash content (left) and heating value (right) of the combustible fraction of CDW compared to construction wood and woody biomass.

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 statewide assessment of urban waste resources currently entering landfills is summarized in Table 1 below[1]. 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 fuel 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. Analysis of this integrated approach will be conducted in the coming year.

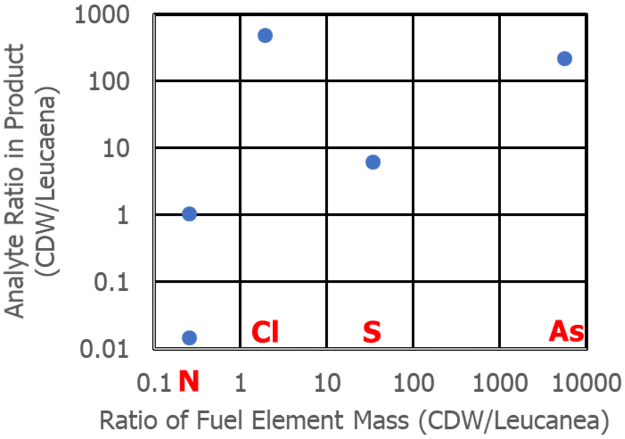

Figure 4. Relative ratios of elements in present in fuels to ratios in the product gas stream.

Future work with ASCENT partners includes:

- Analysis of feedstock-conversion pathway efficiency, product slate (including co-products), maturation;
- Scoping of techno-economic analysis (TEA) issues;
- Screening level greenhouse gas (GHG) life cycle assessment (LCA);
- Identification of supply chain participants and partners;
- Continued stakeholder engagement;

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

County	Maui	Kaua‘i	Hawai‘i	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

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

- Acquiring transportation network and other regional data;
- Evaluating infrastructure availability; and
- Evaluating feedstock availability.

Exploration of Biomass Feedstocks for Hawai‘i

Figure 5 shows the breakdown of land use of the nearly 2 million acres of agricultural lands in Hawai‘i[2]. With the shuttering of much of the cane sugar and the pineapple industries, this total has dropped further. 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 Hawai‘i 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 6).

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.

All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions.

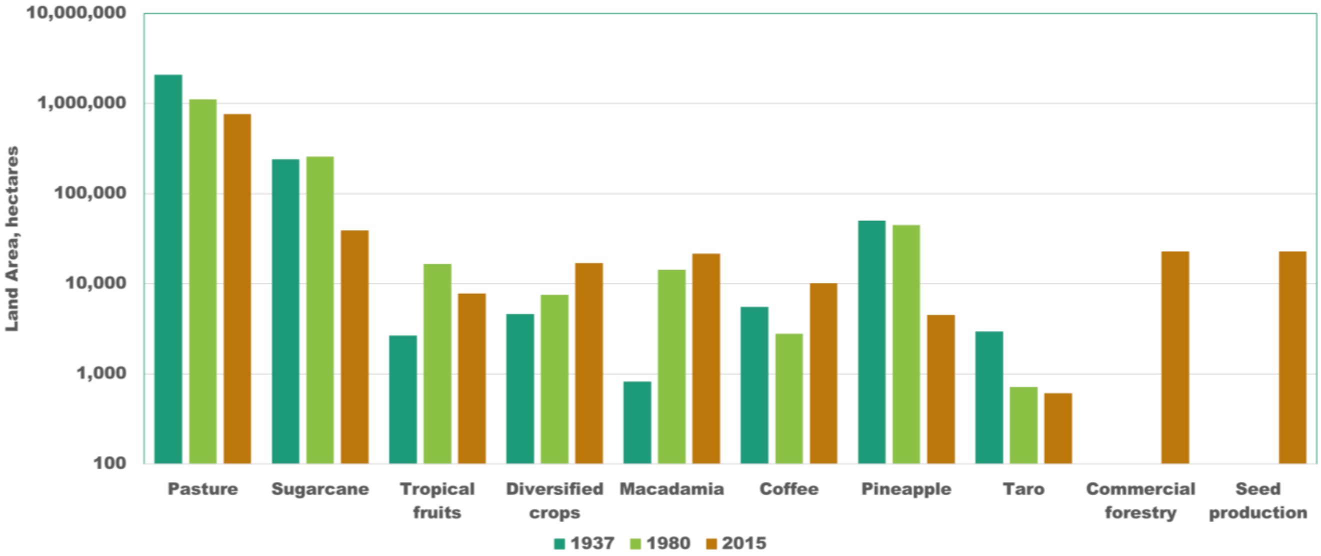

Figure 5. Breakdown of agricultural land use in Hawai‘i; in 2015, approximately 100,000 acres were harvested.

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[2] Adapted from data in Melrose, J., R. Perroy, S. Cares. 2015. *Statewide agricultural land use baseline 2015*. Prepared for the Hawai‘i Department of Agriculture. Honolulu, Hawai‘i.

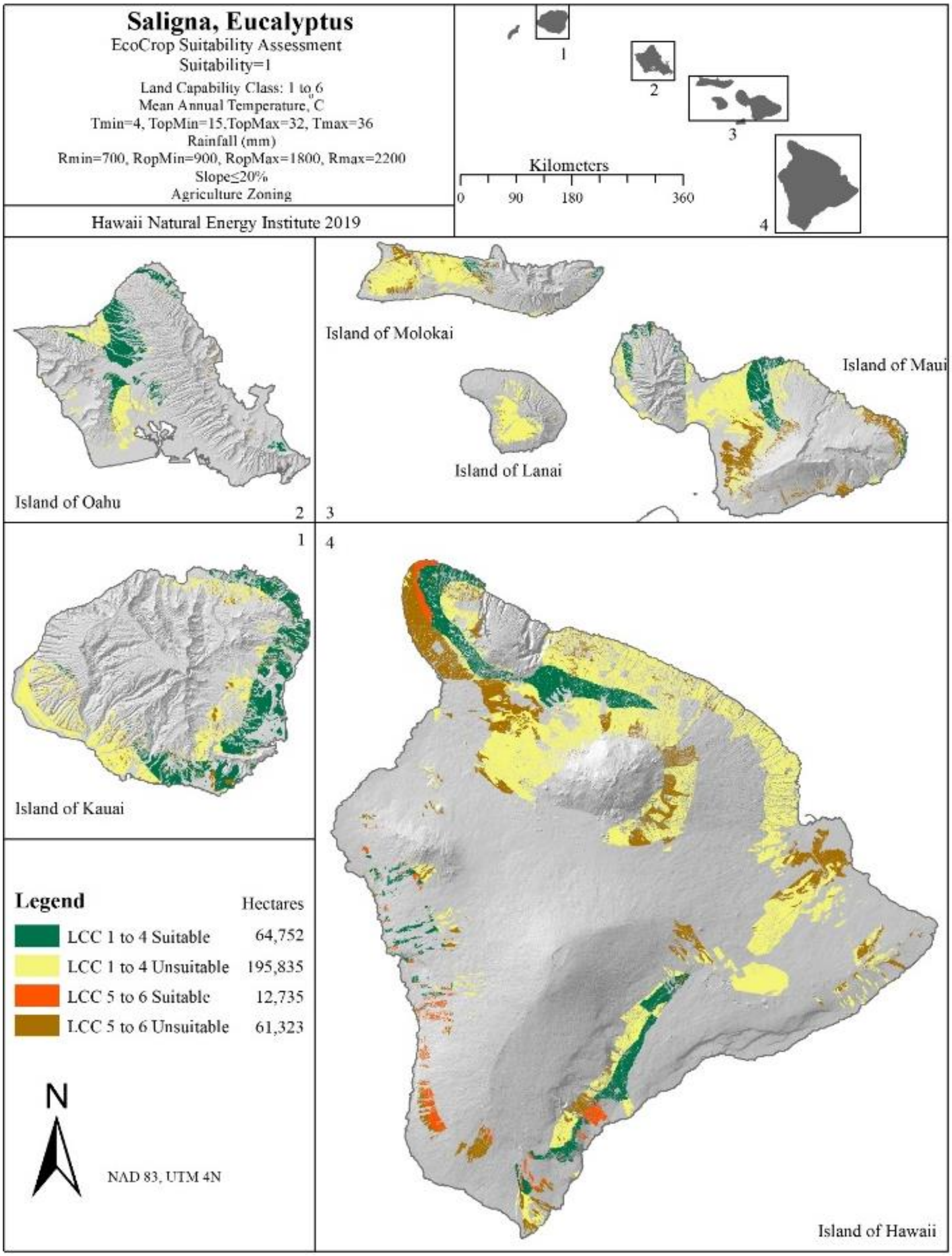

Figure 6. EcoCrop assessment of Saligna, Eucalyptus.

Results of the analyses are shown in Figure 7. 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 service 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 Hawaiʻi at Hilo (UH Hilo) for the Hawaiʻi 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.

Pongamia production 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

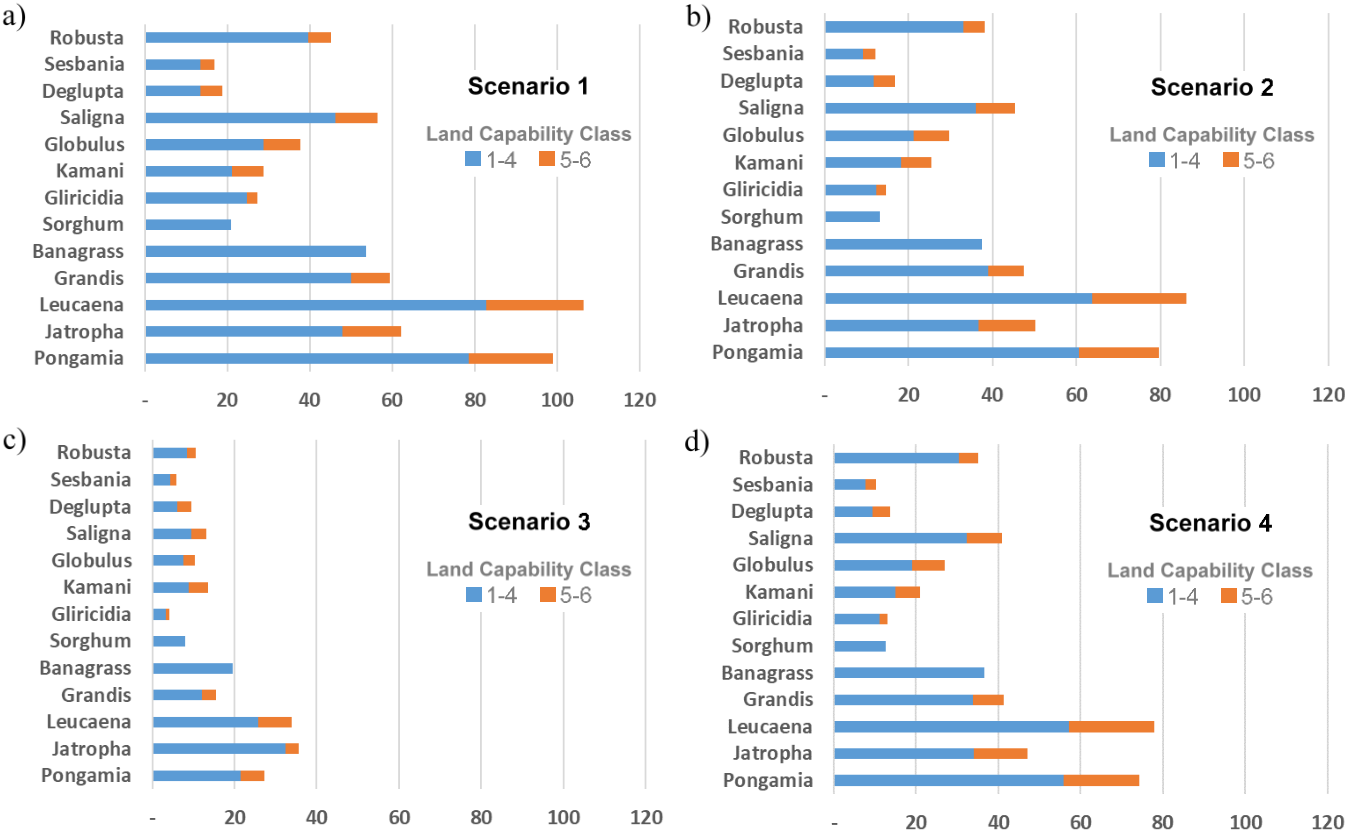

Figure 7. SAF potential (million gallons per year) for 13 energy crop feedstocks under four scenarios: (a) agricultural zoning, slope less than 20%, (b) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems, (c) agricultural zoning, slope less than 20%, exluding land 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.

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

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 location using equation (1).

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

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 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.

$$C_{ik} = \left(\frac{Tkm_i - Tkm_{min}}{Tkm_{max} - Tkm_{min}}\right)_k \quad (2)$$

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 8 and 9 for brownfield and greenfield locations, respectively.

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.

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.

Invasiveness Assessment

Pongamia (*Millettia pinnata*) (Figure 10) is a tree, native to the tropics, that bears an oil seed and has plantings established on Oʻahu. Under this project, an observational field assessment of trees in seven locations on Oʻahu 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 Oʻahu. Because of its limited seed dispersal and low rates of seedling establishment beyond the canopy, 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 Oʻahu, 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 Hawaiʻi***" summarized this work and is available on HNEI's website.

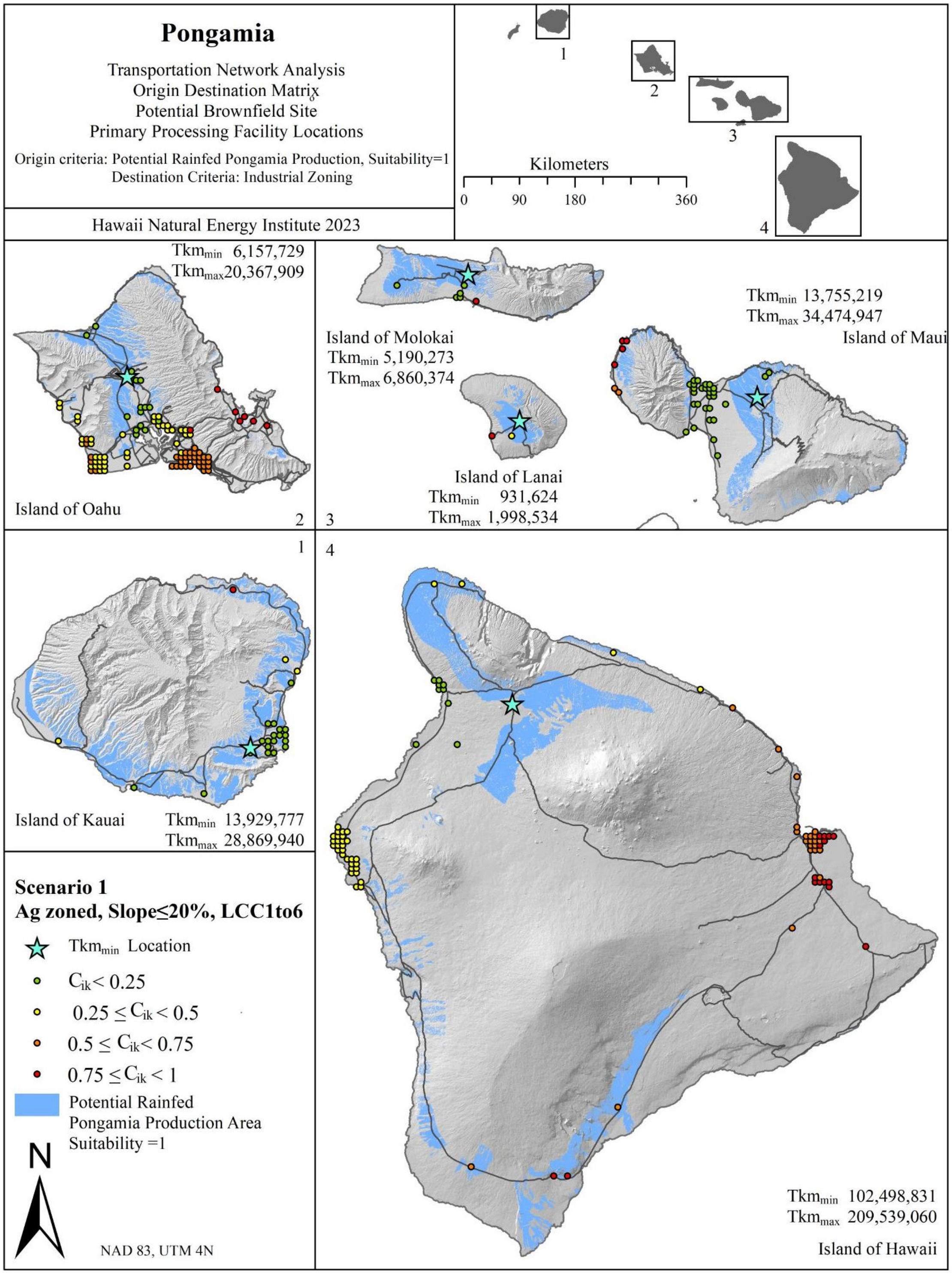

Figure 8. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central <u>brownfield</u> processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability 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 $C_{ik} = 0$.

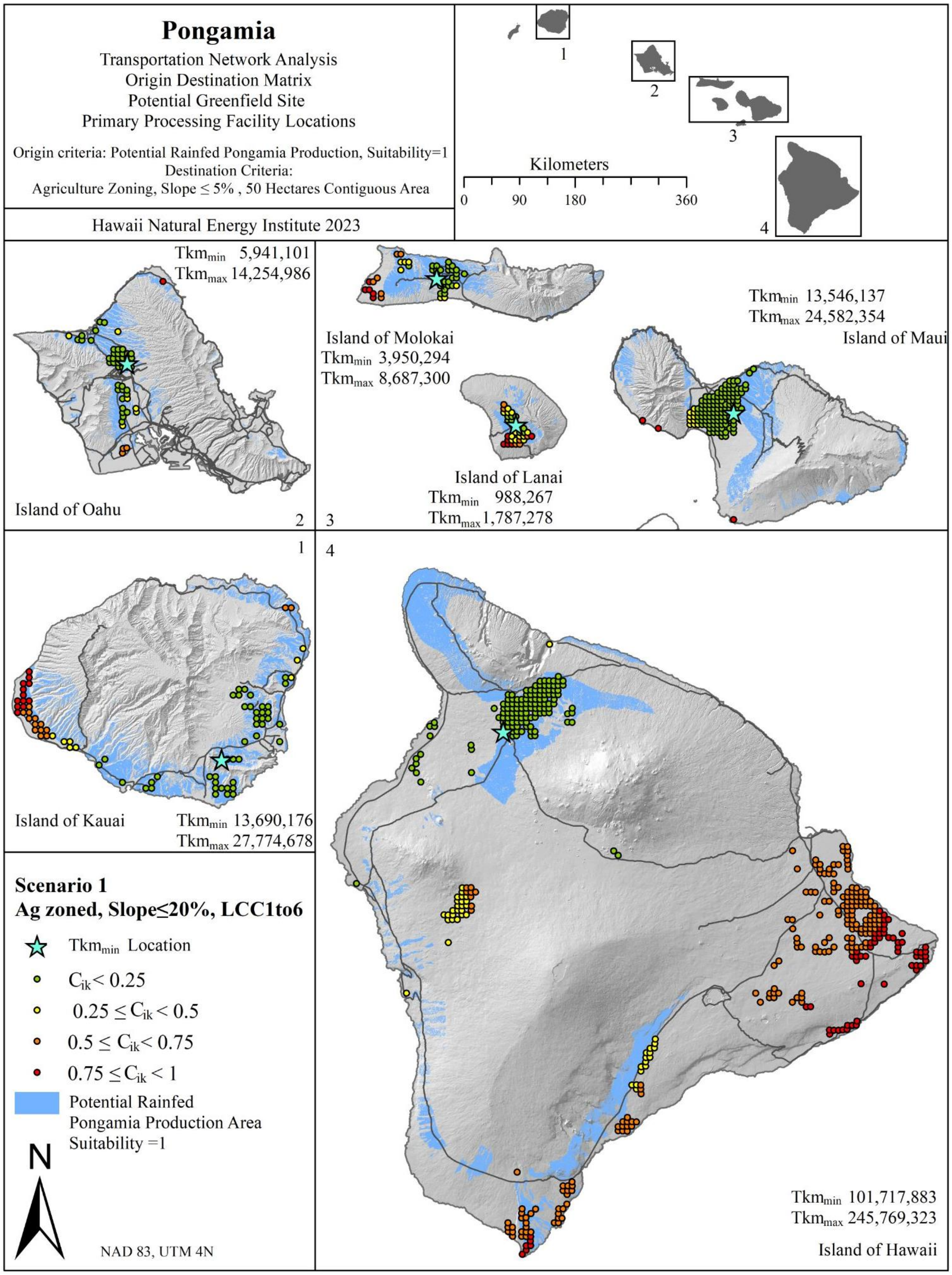

Figure 9. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central greenfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability 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 $C_{ik} = 0$.

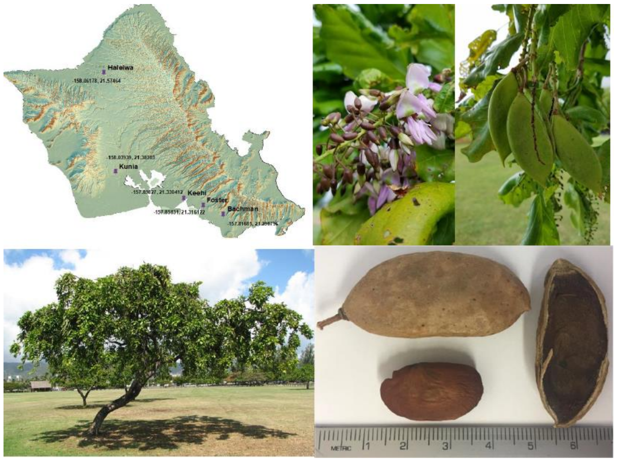

Figure 10. Locations and images of Pongamia.

Figure 11. Pathways from Pongamia seed pods to fuel.

Fuel Properties

Pongamia is a potential resource for renewable fuels in general and sustainable aviation fuel in particular. This physicochemical properties of reproductive material (seeds and pods) from pongamia trees grown in different environments at five locations on Oʻahu were characterized (Figure 11). 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 Hawaiʻi** in the *ACS Omega* journal.

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 12). 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 *Fuel* journal, respectively.

Figure 12. Laboratory scale leaching and torrefaction test equipment.

Other Feedstocks

Other potential feedstocks for Hawaiʻi, 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 Hawaiʻi** in the *ACS Omega* journal.

Summary of SAF Production Potential Estimates

Table 2 compares the SAF technical production potential from urban wastes, oil seeds, grasses, and trees by island with 2018 petroleum jet fuel use data for the state. The use of SAF is currently limited to ≤50% blends with petroleum jet fuel. SAF production potentials from urban wastes range from 1 to 12% of 2018 petroleum jet fuel use by island. Energy crop production potentials range from 0.5 to 108.8% of 2018 petroleum jet fuel use by island. The largest mismatch for urban waste and energy crop potentials occurs in Honolulu, which has the highest jet fuel consumption. The energy crop SAF production potentials are more closely aligned to current petroleum jet fuel consumption on the outer islands under the most optimistic production scenario (see Figure 7a). We would like to note that totals in Table 2 do not include production on Molokaʻi and Lānaʻi.

Funding Source: Federal Aviation Administration; Energy Systems Development Special Fund

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Table 2. Summary of 2018 jet fuel use by island and technical production potentials from urban resources and energy crops (all values in million gallons per year, numbers in parentheses are % of 2018 island fuel use).

	Maui	**Kauaʻi**	**Hawaiʻi**	**Honolulu**	**Total**
Fuel Burn 2018	81	33	50	513	677
Sustainable Aviation Fuel Technical Potentials					
Urban Waste	6 (7.3)	2 (6.7)	6 (11.5)	9 (1.8)	23 (3.4)
Energy Crop, Scenario 1, Suitability >0.5, Not Mutually Exclusive					
Oil Seed	14 (17.7)	13 (40.0)	50 (100.7)	9 (1.7)	86 (12.8)
Trees	16 (19.8)	15 (44.6)	54 (108.8)	9 (1.7)	94 (13.9)
Grasses	8 (9.7)	15 (45.2)	28 (56.1)	3 (0.5)	53 (7.9)