

Supplementary Information: Methods

Site description:

He'eia is a model system for addressing ridge-to-reef sustainability and resilience in Hawai'i and beyond, with the work of three non-profits and many associated groups and volunteers dedicated to its revival as an abundant ridge-to-reef social-ecological system. In addition to Kāko'o 'Ōiwi, who manage 1,600,000 m² of wetland and upland areas, Paepae o He'eia works to restore a traditional downstream fishpond that also provides food production and socio-cultural, and community benefits. Within this broader social-ecological systems context, Kāko'o 'Ōiwi's current conceptual management plan includes wetland and stream restoration; restoration of lo'i kalo; upland agroforestry production of traditional medicinal, ornamental, and food crops; a poi mill for taro processing; retention ponds, including through the use of wetland fish ponds (loko i'a); as well as community and cultural centers for educational and cultural programs [1]. They aim to do this in the most environmentally friendly way possible, including through utilizing renewable energy sources and improving terrestrial, aquatic, and marine habitat.

Kāko'o 'Ōiwi aims to return the wetland area to productive agricultural, cultural, and educational use [1,2]. Since 2010, the non-profit has a 38-year lease from the Hawai'i Community Development Association and in 2011 the area was designated the He'eia Community Development District, with the mission of facilitating cultural practices, culturally appropriate agriculture, education and natural resource restoration [2]. They have worked to restore lo'i kalo since 2008 and with the help of volunteers and a family program have successfully restored ~7,500 with 20 lo'i, built infrastructure to access the wetland for additional plots, and created ~40,000 m² of other management areas including diversified crops, a poi mill, retention basins, and community areas). They seek to restore another ~500,000 m² in the next 20 years alongside a series of other restoration activities (agroforestry, wetland restoration) [1].

The mission of Kāko'o 'Ōiwi is to “perpetuate the cultural and spiritual practices of Native Hawaiians,” of which restoring lo'i through a biocultural approach is a central part. Given the links between lo'i restoration and stream and 'auwai (traditional diversion channels) flow and links to the freshwater connectivity and native fish populations as well as downstream fish pond and reefs and fisheries, the social-ecological impacts of this restoration are also of central interest. In particular, there is strong interest in understanding how lo'i restoration influences water quality, in the form of sediment and nutrient concentrations, as these have important implications for the downstream fish pond and for coral reefs and fisheries, which are also important for local food

production and culture. The restoration proposes to divert the surface water through the restoration of a complex 'auwai system that delivers water to flooded fields and allows for connectivity of freshwater fish and invertebrate species. Currently, most of the surface flow bypasses the wetland and directly empties out into Kāne'ōhe Bay and the downstream fishpond. Much like constructed wetlands, the wetland presents an opportunity to create more pathways for water to filter through the system; divert flow from big flood events to more areas of the wetland during storms; and allow for longer residence times and increased sediment and nutrient retention during baseflow. Restoring lo'i kalo entails clearing existing invasive grasses and sedges, excavating shallow basins, and restoring a wetland and flooded plain agricultural system. Such a system may have a higher flood mitigation and sediment and nutrient retention potential [2,3], with positive effects for downstream marine social-ecological systems (fish ponds and coral reefs) [4].

Community and cultural values methods

Kāko'o 'Ōiwi's model of restoration includes a family or 'ohana program where local families are given access to a lo'i to clear, cultivate, and harvest kalo. This program began in 2016 and Kāko'o 'Ōiwi hopes to continue to grow the program into the future granting lo'i kalo patches to more families over the upcoming years. There are currently 11 families participating, with plans to expand. The mission of the program is to perpetuate cultural practices of Native Hawaiians through traditional agriculture to reconnect kānaka (Native Hawaiians) to the land and provide opportunities to farm. As such, the mission is well-aligned with biocultural restoration approaches.

To understand the participant families' perspectives and experiences with the programs, we conducted semi-structured, in-depth interviews with 8 of 11 participant families following an informal gathering between the researchers, participants, and Kāko'o 'Ōiwi staff. Interviews were conducted while working with the families in the lo'i for 2-3 hours. Interviews focused on understanding how and why families decided to participate, perceived outcomes or changes that occurred from participation, recommendations for improving the program, and perceptions of social and ecological processes that support and influence their work in the lo'i. While we began with a set of questions (listed below), we allowed and encouraged conversations to move towards what interviewees were most interested in discussing.

Interviews were recorded in the field and transcribed, following University of Hawai'i Institutional Review Board procedures. Quotes and themes were coded according to [3] et al. (2017)'s Hawai'i-based cultural ecosystem service framework that includes four main categories: 'Ike (knowledge); Mana (spiritual landscapes); Pilina Kānaka (social

connections); and Ola Mau (physical and mental well-being). When interviewees talked about themes and benefits that did not neatly fit within the framework, we created new categories. Written results were provided to participants for comment and a follow-up workshop was held in July 2017 with participating families (attended by 4 families) to return results and discuss and refine emergent themes.

Guiding questions for interviews were:

What about coming to this lo‘i do you value?

What influences you to use the landscape in this way?

How does He‘eia stream sustain you and this ‘āina?

Crop Yield Methods:

Banana

Data on banana production and prices in Hawai‘i have been collected by the United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS) since 1949 [4–6]. Annual harvested acreage has fluctuated between 2,225,773 and 6,029,821 m² over the period 1949-2016, while annual production has varied from 2028 to 13,154 kg. Yield (kg m⁻²) has also, therefore, displayed large fluctuations, ranging from 0.58 to 2.39 kg m⁻², with a mean value of 1.27 kg m⁻². Farm prices for bananas in Hawai‘i have been trending upward over the same period, reaching a peak of \$2.23 kg⁻¹ in 2016, the most recent year for which USDA survey data was available.

The costs of banana production were estimated based on a report detailing the economics of commercial banana production in Hawai‘i [7]. Operating costs included planting, maintenance, fertilization, weed control, pest control, irrigation, operating interest, harvest, grading and packing, and shipping costs. Ownership costs included management resources, capital resources, land resources, and a price/yield risk factor. After adjusting for inflation, the estimated total cost of production was \$1.50 kg⁻¹.

Scenarios were developed based on the United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS) historical survey data [4–6]: low yield (0.58 kg m⁻²), medium yield (1.27 kg m⁻²), and high yield (2.39 kg m⁻²). In all scenarios, we assumed a farm price of \$2.34 kg⁻¹ [6] and production cost of \$1.50 kg⁻¹ [7].

Breadfruit

Studies examining the life cycle and potential crop productivity of breadfruit in Hawai'i [8–10] have reported wide ranges of both annual yield (50-700 fruits tree⁻¹) and fruit weight (0.23-4.99 kg fruit⁻¹). Years until maturity (fruit-bearing age) were also reported to vary from two to seven years, depending on whether trees were planted from seed or grafted. Once mature, trees are expected to produce at peak fruiting capacity from as little as 10 to as many as 60 years. Because breadfruit has not been historically produced commercially in Hawai'i at large scales, market data is sparse. A recent report on Hawai'i tropical fruits and crops [11] estimated that 1100 breadfruit trees were harvested in 2016, yielding 20,412 kg of fruit at a farm price of \$2.45 kg⁻¹.

For the same reasons that breadfruit market data is largely unavailable for Hawai'i, publicly available commercial breadfruit production cost data for Hawai'i is, to the authors' best knowledge, nonexistent at the time of this writing. Production costs were projected based on an economic analysis of jackfruit [12], which is in the same family (Moraceae) as breadfruit. Growing costs, which apply to the number of trees regardless of fruit-bearing capability, include fertilization, irrigation, pest control, weed control, and pruning. Harvesting costs, which apply to the fruits produced, include picking, packing, and delivery. After adjusting for inflation, annual growing costs totaled \$17.79 tree⁻¹ and annual harvesting costs totaled \$0.29 kg⁻¹ in 2018 dollars.

We developed three scenarios: low density and yield (0.0049 trees m⁻², 40.82 kg tree⁻¹), medium density and yield (0.0057 trees m⁻², 180.53 kg tree⁻¹), and high density and yield (0.0062 trees m⁻², 394.17 kg tree⁻¹)—which were constructed based on the range of planting density, tree yield and fruit weight data reported in studies examining the life cycle and potential crop productivity of breadfruit in Hawai'i [8–10]. In all scenarios, we assumed that trees reach fruiting age after two years and peak fruiting capacity is maintained over the 20-year management period. We also assumed, after adjusting for inflation, a farm price for breadfruit of \$2.58 kg⁻¹ [11], growing cost of \$17.79 tree⁻¹, and harvesting cost of \$0.29 kg⁻¹ [12].

Taro

Two taro production scenarios were developed through an iterative discussion process with staff at Kāko'o 'Ō'iwi. In scenario 1, we assumed a yield of 1.12 kg m⁻², a value of \$5.51 kg⁻¹ for raw taro, an average value of \$7.03 kg⁻¹ if the taro is further processed into additional products (e.g. poi, a Hawaiian food prepared from the cooked corms of taro that are pounded or mashed into a consistency of a paste or thick liquid) before being sold, and a production cost of \$10.14 kg⁻¹. In scenario 2, yield was increased to 1.79 kg m⁻², raw taro value remained at \$5.51 kg⁻¹, the value of additional taro products was increased to \$10.34 kg⁻¹, and production costs were decreased to \$6.33 kg⁻¹. In both

scenarios, 6475 m² of taro were added each year, such that total acreage reached 125,453 m², or 25% of the total farm area, by year 20. We estimated revenue, costs and profits over 20 years for both scenarios and also considered the case where volunteer family labor reduces production costs by 15%.

Energy methods:

Avoided energy inputs

Production of N-based fertilizers through the Haber-Bosch process combines atmospheric N with hydrogen under high pressure and temperature to form ammonia and is estimated to require between 10.3 and 16.7 kWh/kg [13].

On-farm solar energy for food processing

[14] et al. (2003) estimated energy consumption for a corn wet milling operation, based on a 100,000 bushel/day facility. Energy input for all processes leading up to the grinding stage (receiving, steeping, steepwater evaporation, first grind, second grind) totaled 0.0254 kWh /kg. We assume that the farm experiences roughly four hours of peak sunlight per day on average [15] and that the mill is run year-round for five days per week on average.

Energy offset from taro production

Growing taro locally in Hawai'i could offset imports. We estimate the fuel needed to ship taro to Hawai'i as a conservative estimate of the energy offset from locally produced taro. Traveling at an average speed of 23 knots [16], we assume that a small (4000 TEU) ship burns 110 tons of fuel per day, a medium (7000 TEU) ship burns 200 tons/day, and a large (10,000 TEU) ship burns 10,000 tons/day [17]. Taro is shipped to Hawai'i, mainly from Fiji [18], whose main port lies 2,084 nautical miles from Honolulu, Hawai'i, requiring 5.02 days of travel at 23 knots. Each container – or TEU – holds 33.2 cubic meters of cargo. Taro weighs 139 kilograms per cubic meter [19], implying that a single container can hold 4.61 tons of taro. A small boat thus uses 0.031 tons fuel per ton taro, a medium boat 0.0322, and a large boat 0.031. A gram of heavy fuel oil produces 41 kilojoules of energy. This information was combined to calculate the energy offset from producing rather than importing the taro produced in the scenarios described above.

Sediment and nutrient methods

Sediment:

Baseflow characteristics of He'eia stream were calculated using 69 years of discharge data (1943 to 2018) available for Ha'iku sub watershed USGS Site 16275000 and 28 years of discharge data available for 'Ioheka'a subwatershed USGS Site 16278000 [20]. We

combined the mean daily discharge of Ha'iku and 'Ioleka'a streams, or 1.4 MGD (2.2 cfs) plus 0.4 MGD (0.67 cfs) totaling 1.8 MGD (2.87 cfs), for the calculations presented in this study.

InVEST Sediment Delivery Ratio (SDR) Model:

We modeled sediment export from imperious surface (C-factor 0.03) and developed open space (C factor 0.01) according to the spatial layout of a suburb similar to the surrounding areas using the InVEST SDR model [21]. We did not use the SDR InVEST model for the current scenario or full restoration scenario because this model does not capture retention of wetland areas.

Sediment export at He'eia stream mouth during baseflow for the current scenario was based on average TSS concentration exported from the wetland (18.5 mg L^{-1} from 2013 to 2017) [22] and combined mean daily discharge of Ha'iku and 'Ioleka'a streams (1.8 MGD (2.87 cfs); [20]), translating to approximately 75 tons yr^{-1} of sediment. We assumed this was 7% of the sediment budget (given that much of export is not associated with baseflow according to [23] et al. 2009's estimates of base versus storm export), which resulted in a total current export of $1070 \text{ tons yr}^{-1}$. Thus current net input and export (2335 tons input and 1070 tons export), resulted in an accumulation of 1265 tons of sediment in the wetland per year.

For the restored agriculture scenario, [24] et al. 2016's accumulation rate for lo'i retention in the agricultural restoration scenario translated to a future accumulation of 1670 tons of sediment per year (for the $595,400 \text{ m}^2$ of retention space available in this scenario). Sediment retention was null in the urban scenario and of the upland areas within Kako'o 'O'iwi from non-native vegetation to urban also increased sediment export by 31 tons yr^{-1} .

Nitrogen

To calculate nitrogen retention within the watershed under current conditions, we used HDOH (2018) data, which show total N concentrations in surface water at sites above and below the wetland (mean (\pm s.d.) as $0.31 (0.1) \text{ mg L}^{-1}$ and $0.16 (0.08) \text{ mg L}^{-1}$, respectively, over four years. This suggest that $\sim 50\%$ of total N is removed from the wetland, which is comparable to nitrogen retention in other wetland studies with wastewater inputs [25,26]. We focus on total N, as the same HDOH study found substantial reductions in both nitrate ($0.19 (0.02) \text{ mg L}^{-1}$ to $0.006 (0.014) \text{ mg L}^{-1}$) and ammonia ($0.014 (0.017) \text{ mg L}^{-1}$ to $0.006 (0.006) \text{ mg L}^{-1}$). These numbers represented export during baseflow conditions, not during storm events when the stream discharge would not be well filtered [27]. We assumed that atmospheric deposition and N fixation are

minimal in the wetland. We considered nitrogen inputs in surface water only, acknowledging that He'eia wetland is fed by groundwater.

InVEST Nutrient Delivery Ratio (NDR) Model:

The InVEST nutrient delivery model estimates nitrogen retention using the concept of nutrient delivery ratio (NDR). The technique provides quantitative values to a risk-based approach, and considers both an estimate of nutrient loading rates and a calculated probability that a nutrient load will reach a stream. Additionally, two transport processes are modeled, nutrient transported by surface flow, the other for subsurface flow [21]. For this work in west Hawaii, we only considered subsurface flow. The model uses a digital elevation model (DEM) to calculate flow paths. from the Hawaii Statewide GIS program. The DEM was additionally processed to remove pits using TauDEM (TauDEM 5.0, <http://hydrology.usu.edu/taudem/taudem5/downloads5.0.html>).

Inputs to the model include land use (C-CAP, 2010, 2.4m resolution), 10-m resolution digital elevation model and a proxy for nutrient runoff, in this case the average annual rainfall [28]. In order to model nitrogen input into the wetland and include land uses that have an impact on nitrogen loads, a custom land use map was generated to include the on-site disposal systems (OSDS), identify lawns and gardens, and include golf courses. In an accompanying biophysical table, N input (kg) per hectare per year was designated for each land use. OSDS was 2000 kg ha⁻¹ y⁻¹, lawns and gardens 50 kg ha⁻¹ y⁻¹ and golf courses 250 kg ha⁻¹ y⁻¹. (For additional parameterization, see SI Table 1). The model was calibrated using a Borselli k parameter of 2.8, as described in [29] et al. (2017). There are 216 cesspools and OSDS systems contribute a total of approximately 4300 kg of N per year [30]. Per [31] et al. (1991), only 19% of water was surface runoff, with 81% as subsurface runoff. The threshold accumulation factor used was 3000.

Description	Land Use Code (CCAP)	C-factor	P-factor	N load	N efficiency	Proportion Subsurface N
Developed High Intensity	2	0.001	1	10	0.1	0.81
Developed Medium Intensity	3	0.01	1	7.5	0.15	0.81
Developed Low Intensity	4	0.02	1	5	0.25	0.81
Developed Open Space	5	0.003	1	50	0.1	0.81
Cultivated Crops	6	0.12	1	100	0.75	0.81
Grassland/Herbaceous	8	0.003	1	3.1	0.99	0.81

Evergreen Forest	10	0.001	1	11.3	0.99	0.81
Scrub/Shrub	12	0.003	1	5.5	0.99	0.81
Palustrine Forested Wetland	13	0.001	1	1.62	0.99	0.81
Palustrine Scrub/Shrub Wetland	14	0.001	1	1.62	0.99	0.81
Palustrine Emergent Wetland	15	0.001	1	1.62	0.99	0.81
Estuarine Forested Wetland	16	0.001	1	1.62	0.99	0.81
Estuarine Scrub/Shrub Wetland	17	0.001	1	1.62	0.99	0.81
Estuarine Emergent Wetland	18	0.001	1	1.62	0.99	0.81
Unconsolidated Shore	19	0.005	1	0	0.75	0.81
Open Water	21	0	1	2.6	0.1	0.81
Golf courses	23	0.003	1	100	0.1	0.81
Cess pools	62	0.02	1	2500	0.1	0.81
Lawns and Gardens	80	0.02	1	50	0.1	0.81

Table S1: Parameterization of InVEST NDR model

Supplementary Information (Results)

Crop yield Figures

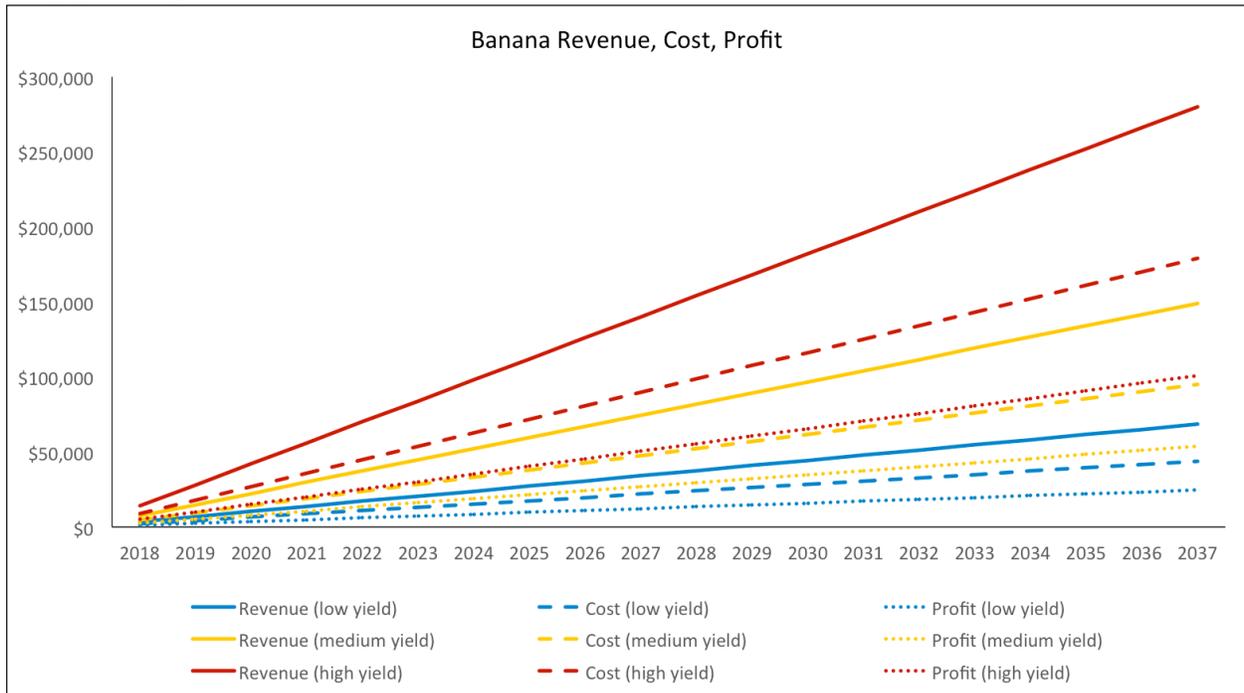


Figure S1. Revenue, costs, and profit of banana with and without family model and under different yield and cost assumptions.

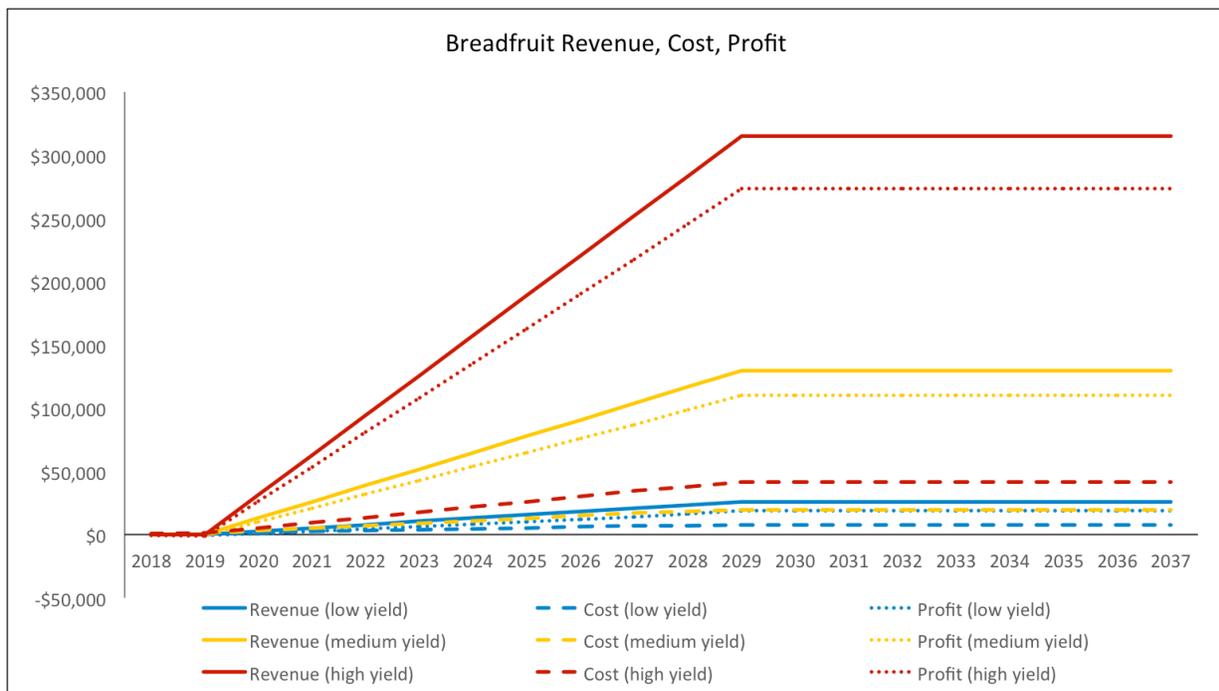


Figure S2. Revenue, costs, and profit of Ulu with and without family model and under different yield and cost assumptions.

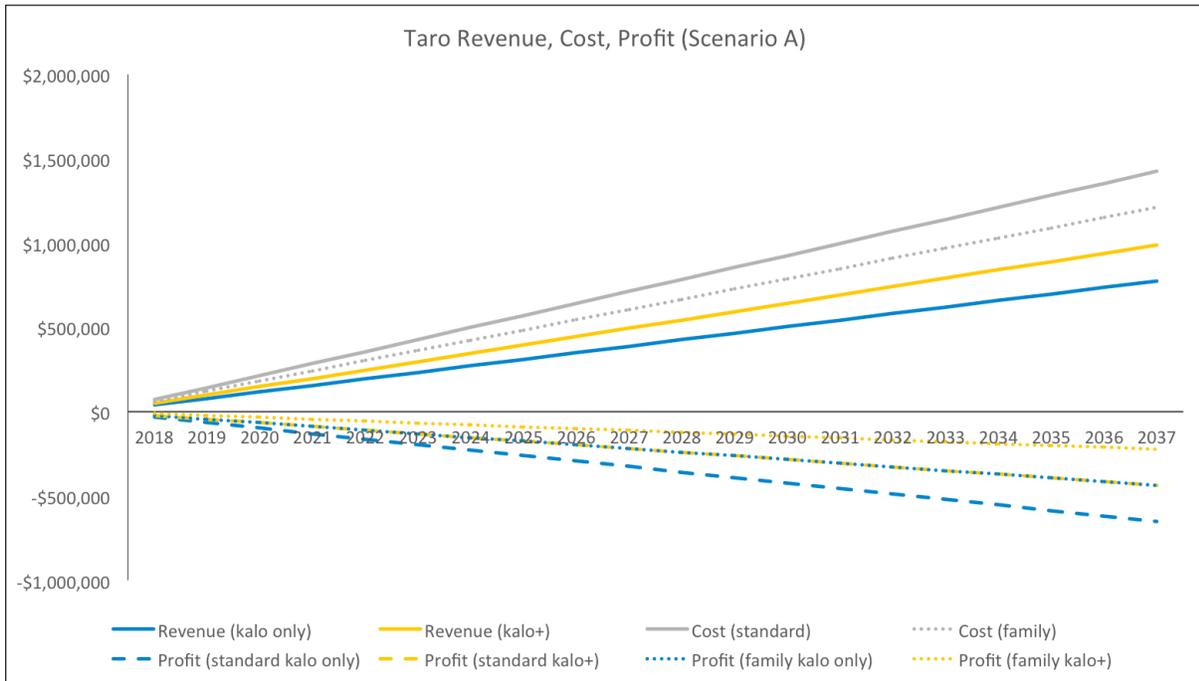


Figure S3 Revenue, costs, and profit of taro scenario 1 (10,000 pounds per acre) with and without family model and with and without additional taro products.

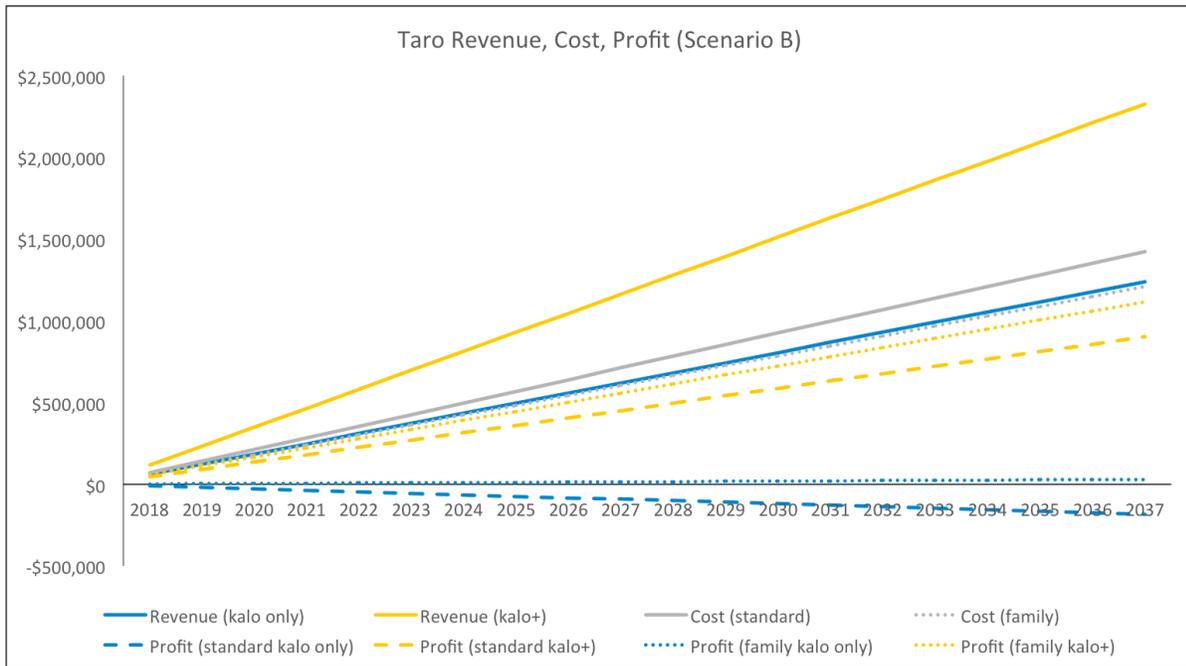


Figure S4: Revenue, costs, and profit of taro scenario 2 (16,000 pounds per acre) with and without family model and with and without additional taro products.

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