Observational field assessment of invasiveness of pongamia (*Millettia pinnata*), a candidate biofuel crop in Hawai‘i

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June 2018

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This work received funding support from the Federal Aviation Administration through the Aviation Sustainability Center (ASCENT), also known as the Center of Excellence for Alternative Jet Fuels and Environment. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA, NASA or Transport Canada.

Summary

Pongamia (*Millettia pinnata*), a tree in the bean family (Fabaceae), is a candidate biofuel crop in Hawai‘i. Pongamia was previously assessed by the Hawaii-Pacific Weed Risk Assessment (HPWRA) and predicted to pose a high risk of becoming an invasive weed in Hawai‘i (HPWRA score = 7, where a score of 6 or higher indicates high risk). Retrospective analyses show that predictive WRA systems correctly identify many major pest plants, but WRA predictions are not 100% accurate. The purpose of this study was to make field observations of pongamia planted around Oahu in order to look for direct evidence that pongamia is escaping from plantings and becoming an invasive weed on Oahu. Seven field sites were visited in varying environments across Oahu. 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 Oahu. 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 Oahu, 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.

Background

The Hawaii Bioenergy Master Plan (HBMP) developed by Abbas et al (2009) identifies potential invasiveness as an important risk to be considered in choosing biofuel crops to be grown in Hawai‘i. Invasive species brought to the Hawaiian Islands have already caused substantial economic costs as well as ecological harm, so serious efforts should be made to avoid introducing or propagating new invasive plants. Weed Risk Assessment (WRA) was identified by HBMP as an established tool for evaluating risk of invasiveness among candidate biofuels. The Hawai‘i-Pacific Weed Risk Assessment (HPWRA) is a modified version of the Australian WRA system which has been adapted and calibrated for use in the Hawaiian Islands (Daehler et al 2003). HPWRA uses a series of questions about a plant’s ecology, history of weediness in other parts of the world, noxious traits, and climatic tolerance to derive a numeric risk score. HPWRA is a predictive tool. Retrospective testing showed that more than 90% of major weeds in Hawai‘i have HPWRA scores of 6 of greater; therefore, discouraging planting or preventing importation of plants scoring 6 or greater is expected to reduce the spread of major pest plants in Hawai‘i. Nevertheless, retrospective testing also showed that some plants that scored 6 or greater do not behave as weeds in Hawai‘i (Daehler et al 2003). Because HPWRA is designed as a predictive tool, it does not take into account actual behavior of a plant species in Hawai‘i in cases where it has already been introduced to Hawai‘i . Therefore, if available, knowledge of a plant’s actual behavior in Hawai‘i can provide valuable supplemental information to evaluate risks that a plant will become a serious weed in Hawai‘i.

Field observations were previously made on several candidate biofuels in Hawai‘i as a means of supplementing predictive information provided by HPWRA (Daehler et al 2012). In some cases where HPWRA predicted a high risk of becoming a weed (score of 6 or higher), field observations, such as escape of plants from cultivated areas and abundant spread of wild populations far from plantings, supported the HPWRA designations of high risk (e.g. seed-bearing arboreal *Leucaena*). However, for some other candidate biofuel crops, no evidence of weedy behavior was observed despite extensive plantings over a long time period (e.g. *Eucalyptus grandis*). Thus field assessments can provide useful information alongside HPWRA scores to make informed planting decisions. Field assessments can also suggest preventative strategies to reduce the risk that any planted species will escape from cultivation and become a weed.

One candidate biofuel that was not assessed by Daehler et al (2012) is pongamia (*Millettia pinnata*). Pongamia is a tree in the bean family (Fabaceae), native to a broad region extending from India to China and northern Australia (a comprehensive listing of pongamia’s geographic range is given by Csurhes and Hankamer 2016). The tree produces oil-rich seeds from which biofuel can be extracted. Pogamia received an HPWRA score of 7, predicting a high risk of becoming a weed. One important contributor to its high HPWRA score is that pongamia has been recorded as a weed of gardens and lawns in southern Florida (Llamas 2003) and disturbed areas, such as roadsides and riparian vegetation in southern Queensland, Australia (Brisbane City Council (n.d.)). It is also recognized as naturalized (not native and growing wild) on the islands of Mauritius and Rodrigues (Indian Ocean), where it is found in coastal habitats including mangroves and estuaries, but there is no concensus that the plant behaves as a weed there (Kueffer and Mauremootoo 2004). Becoming naturalized somewhere in the world with a tropical environment similar to Hawai‘i, as well as being reported as a weed of disturbed areas increases pongamia’s HPWRA score by several points. Other factors that added to pongamia’s HPWRA score were toleration of mutilation (regrowth after cutting), ability to fix nitrogen, and ability to self-pollinate without specialist pollinators.

Pongamia was introduced to Hawai‘i around a century ago (before 1867 according to St John (1973)), presumably by William F. Hillebrand, as a very large pongamia tree still exists at Foster Botanical Garden in Honolulu (Hillebrand’s former home site). Although historically, pongamia plantings have been fairly limited in Hawai‘i, for this study, known plantings on Oahu were visited in order to determine whether pongamia has become naturalized and to look for evidence that pongamia is spreading away from the plantings or exhibiting behaviors that suggest it may be an invasive pest plant in Hawai‘i .

Methods

A total of seven different pongamia sites were visited on Oahu between May 15 and May 25, 2018 (Figure 1). These sites encompass a range of climates (dry to wet), allowing for observations of pongamia’s behavior under different growing conditions. At each site, line transects were established and surveys along the transects were used to quantify any escaping plants (seedlings and / or root suckers). Observations were also made on plant phenology and seed pods. The vegetation surrounding pongamia plantings was characterized in order to identify the types of habitats where pongamia plantings occur, as well as successful weedy plants in the vicinity of each planting.

Figure 1. Overview of pongamia locations visited on Oahu, Hawaii: 1) Hawai‘i Agriculture Research Center (HARC) (TerViva plantings), 2) North Shore (TerViva plantings), 3) Ke'ehi Lagoon Beach Park, 4) University of Hawaii Manoa, 5) Foster Botanical Garden, 6) Waimea Valley, 7) Round Top Drive.

Results

Hawai‘i Agriculture Research Center (HARC), Kunia Road, Waipahu (TerViva plantings)

A total of around 38 trees were observed planted in two different irrigated areas, each area consisting of a single row of trees. The trees were fairly young (planted sometime between 2012 and 2014), and some of the trees showed clear evidence of being cut back for vegetative propagation (Elisabeth Beagle, personal communication). The plants readily grew back after cutting (Figure 2). No flowers were observed, but some trees had pods, and pods were observed scattered on the ground (Figure 4). Many pods had been harvested (Elisabeth Beagle, personal communication). Transects were walked parallel to the two tree rows, searching for pongamia seedlings at a distance of 2-4 m from the mother tree trunks. No pongamia seedlings were observed (Table 1). Areas directly beneath the tree canopies were also searched and no pongamia seedlings were observed. Other weedy plants were abundant in the vicinity of the trees (Figure 3), including Guinea grass (*Megathyrsus maximus*), southern sandbur (*Cenchrus echinatus*), beggar-ticks (*Bidens pilosa*), and uhaloa (*Waltheria indica*). These neighboring weeds were indicative of a dry, disturbed environment, and these weeds were abundant mainly in the vicinity of irrigation. Plowed areas and dirt roads were also surveyed within 5 m of the pongamia trees, but no pongamia seedlings were found; these latter areas generally lacked vegetation, probably due to persistent disturbance and a harsh, dry environment outside of the range of irrigation (Figure 5).

Figure 2. Regrowth of a young pongamia tree after repeated cutting.

Table 1. Transects surveyed at Hawai‘i Agriculture Research Center (HARC)

Transect #	Length(m)	Width(m)	Area searched(m^2)	Pongamia seedlings
1	80	2	160	0
2	80	2	160	0
3	30	2	60	0
Total			380	0

Figure 3. Pongamia planted in a row at HARC with neighboring weedy vegetation, dominated by Guinea grass and southern sandbur; the adjacent dry dirt road is free of vegetation. No pongamia seedlings were found.

Figure 4. Area beneath a pongamia tree canopy showing pongamia seed pods that have fallen on geotextile cloth. Weeds such as beggar ticks are visible. No pongamia seedlings were found.

Figure 5. View of disturbed dryland adjacent to the pongamia plantings at HARC

North Shore site (TerViva plantings)

Pongamia trees at this site were planted into around nine blocks totaling around 20 hectares (50 acres) (Elisabeth Beagle, personal communication). All trees were young (planted 2013-2017); however, some of the older plantings had produced pods, some of which were observed on the ground. Some trees were beginning to flower and some leaves showed evidence of skeletonization by insects (probably the Chinese rose beetle (*Adoretus sinicus*)). The trees were being grown with drip irrigation, and rows were sometimes covered with geotextile ground cloth. Grasses and other weeds were abundant between rows (Figure 6). A sample of five rows of pod-producing trees was haphazardly selected, and 100 m x 2 m transects were surveyed parallel to the rows. The transects included areas beneath the tree canopies (Figure 7) as well as neighboring weed-covered areas. A total of one pongamia seedling was observed (Table 2, Figure 8). The single seeding was found less than 1 m from the trunk of a mother tree, within the area being fed with drip irrigation. A broader area along the neighboring dirt road surrounding the fields was also searched by walking, but no pongamia seedlings were found. Vegetation between rows was dominated by Guinea grass (*Megathyrsus maximus*) with scattered horseweed (*Erigeron canadensis*) in gaps in the ground cloth. Seedlings of the invasive Brazilian pepper tree (*Schinus terebinthifolius*) were also frequently observed within the pongamia plantation. These plants suggest an environment with less extreme heat and drought, as compared to the HARC site. Because the pongamia plantings were very young at this site, there have been relatively few seeds released into the environment; nevertheless, no evidence was found of pongamia seedlings escaping from planted areas.

Table 2. Transects surveyed at North Shore TerViva plantings

Transect #	Length(m)	Width(m)	Area searched(m^2)	Pongamia seedlings
1	100	2	200	0
2	100	2	200	1
3	100	2	200	0
4	100	2	200	0
5	100	2	200	0
Total			1200	1

Figure 6. View of a North Shore planting row showing drip irrigation line and dense Guinea grass between rows.

Figure 7. Fallen pods beneath a pongamia tree, along with Guinea grass seedlings, North Shore.

Figure 8. A single pongamia seedling was found in a search of 1200 m^2. This seedling was located on irrigated soil within 1 m of a pongamia trunk, North Shore.

Ke'ehi Lagoon Beach Park

Fourteen mature pongamia trees were observed at Ke'ehi Lagoon Beach Park. The trees were growing < 5 m above sea level, 100-150 m from the edge of the water (Figure 9). The trees were in the open, surrounded by low-mowed Bermuda grass (*Cynodon dactylon*) and exposed to strong winds and full sun (Figure 10). Some trees had yellowed leaves, possibly due to heat, drought or salt stress, while others had skeletonized leaves, probably due to attack by the Chinese rose beetle (*Adoretus sinicus*). Some pongamia trees were flowering; flowers were being visited by honey bees (*Apis melifera*) and Sonoran carpenter bees (*Xylocopa sonorina*). At the time of the visit (early afternoon) the grounds were receiving supplemental water from a sprinkler system, but periods of drought were evidenced by the condition of the park's Bermuda grass, which had mostly died back (Figure 10). Around half of the trees had pods, and pods were also scattered on the grass beneath the canopy of some trees (Figure 11). Wind was predominantly blowing towards the ocean. A series of transects were surveyed from the trees towards the ocean, as well as between pongamia trees, but no pongamia seedlings or root suckers were observed in the grass. A restroom structure was located around 20 m east of the main group of trees (Figure 9); wind-protected, shady areas near the restroom were searched for pongamia seedlings but none were found. Since pongamia can tolerate saline soils and saline water (Arpiwi et al 2013), and pongamia is known to be water dispersed (Nakanishi 1989), the shoreline in the vicinity of the

trees was searched for escaped pongamia seedlings or saplings (Figure 12), but no pongamia plants were found. Other naturalized plants were observed colonizing the shoreline, including buttonwood (*Conocarpus erectus*) and red mangrove (*Rhizophora mangle*). Dry shrubland neighboring the park was dominated by kiawe (*Prosopis pallida*) and haole koa (*Leaucaena leacocephala*), indicative of the hot, dry climate in the area. No escaped pongamia plants were seen in this neighboring dry shrubland (Figure 9; furthest transect towards the west).

Figure 9. Map of Ke'ehi Lagoon Beach Park showing the location of pongamia trees (hashed areas) and surveyed transects (black solid lines) Transects were 2 m wide.

Figure 10. Three pongamia trees at Ke'ehi Lagoon Beach Park with brown Bermuda grass below. No tree seedlings of any type were seen in the Bermuda grass, and no pongamia root suckers were found.

Figure 11. Fallen pods were seen on the Bermuda grass. Many pods contained normal-sized, presumed viable seeds, in spite of dry, hot conditions and likely salt stress at this site.

Figure 12. View of the water and dryland adjacent to pongamia trees. The pongamia trees are not clearly visible in the photo but are located around 150 distance, towards the left side. No pongamia seedlings or saplings were found along the shoreline or in the adjacent dryland.

University of Hawaii Manoa Campus

A single large (~ 20 m) pongamia tree was observed on the University of Hawaii Manoa campus near Bachman Hall (Figures 13 and 14). The tree had mostly green pods and some remnant inflorescences. However, the ground beneath the tree was littered with thousands of brown pods. Many pods were flat (without a viable seed), but 10-20% of pods contained normal sized seeds. Thousands of pods were heaped up against the wall of Bachman Hall, beneath a hedgerow of Carruthers' falseface (*Pseuderanthmum carutheri)* (Figure 15, transect 1 on Figure 13), which received sprinkler irrigation. This hedgerow provided a shady, moist environment. A similar environment existed beneath a sparse row of Cardinal's guard shrubs (*Odontonema cuspidatum*) planted along an adjacent wall of Bachman Hall (Figure 13, transect labeled "2"). During the survey of these two transects, totaling around 30 m length and around 0.6 m transect width, 11 pongamia seedlings were found, ranging in size from 2 cm to 25 cm in height. No seedlings were observed growing in the grass or disturbed, moist soil beneath the canopy of the mother tree, although pods were abundant there (Figure 16). Additional transects were searched outside the canopy of the mother tree, along the roadside, and in the campus lawn. Seedlings of various weedy and invasive shrubs and herbs were noted growing in moist, semi-shaded areas beneath shrubs, including Fukien tea (*Carmona retusa),* obscure morning glory (*Ipomea*

obscura), ivy gourd (*Coccinia grandis*), and Oriental false hawksbeard (*Youngia japonica*). Only single pongama seedling was found in these areas, located around 25 m from the trunk of the mother tree and around 15 m outside the canopy of the mother tree (Figure 13, arrow). This seedling was growing in semi-shade at a corner of Bachman Hall, beneath a traveler's palm (*Ravenala madagascariensis)*.

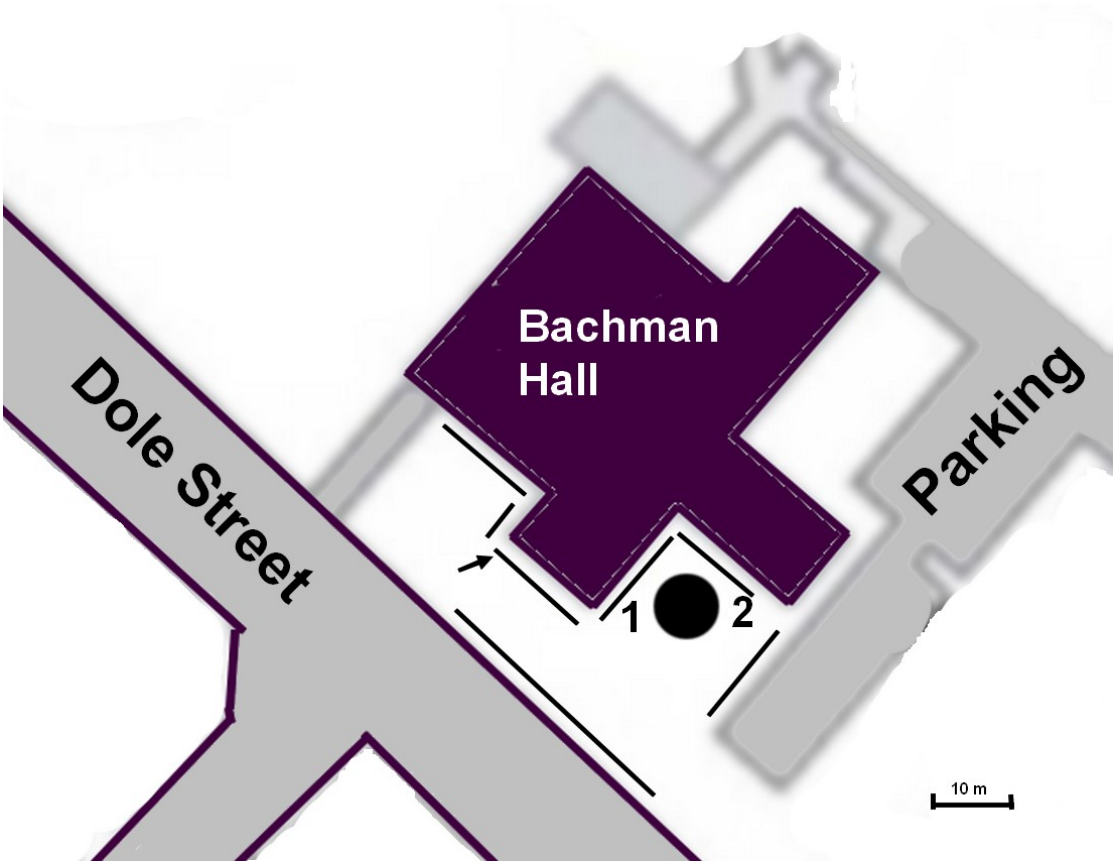

Figure 13. Location of the pongamia tree (round solid circle) at the University of Hawaii at Manoa. Surveyed transects are indicated by solid thin black lines (transect width was 0.6 - 1 m). The canopy extends over transects 1 and 2. The location of the single pongamia seedling found outside the canopy of the mother tree is denoted by the arrow.

Figure 14. The pongamia tree at the University of Hawaii at Manoa. Hedge rows corresponding to transects 1 and 2 are visible.

Figure 15. Pongamia pods piled up beneath Pseuderanthum shrubs (transect 1), UH Manoa campus. A single, light green pongamia seedling is visible at the far left.

Figure 16. An area of disturbed, moist soil beneath the pongamia canopy, UH Manoa campus. No seedlings were seen in this disturbed area, although pods are clearly broken (probably by a lawnmower) and seeds are exposed.

Foster Botanical Garden, Honolulu

A single large (~ 20 m) pongamia tree was observed at Foster Botanical Garden, growing next to a building that houses restrooms (Figure 17 and 18), near the garden border with the H1 freeway. Thousands of brown pods were observed on the ground beneath the canopy. The canopy was overhanging part of the restroom building and also overhanging a wall separating the garden from the H1 freeway. Three transects were established leading away from the tree in different directions (Figure 17). Along transect 1, pongamia seedlings were found only beneath the canopy; the maximum seedling density was 4 m^{-2} (Figure 19). Beyond the canopy along transect 1 (~ 5 m) was an area of sparse Heliconia plantings, and no pongamia seedlings were seen in this area (Figure 19), although seedlings of several common invasive plants were seen, including African tulip tree (*Spathodea campamulata*), Surinam cherry (*Eugenia uniflora*), yellow alder (*Turnera ulmifolia*), and Fukian tea (*Carmona retusa*). Along transect 2, pongamia seedlings reached higher densities (as high as 16 m^{-2}) (Figure 20 and 21), however, most of these seedlings were directly under the canopy of the mother tree (within 6 m of the

trunk, while the canopy extended around 5 m from the trunk) (Figure 20). Only one seedling was found clearly beyond the canopy of the mother tree, at 22 m from the trunk (Figure 20 and 22). In order to explore the possibility of longer distance establishment in this direction, transect 2 was extended to almost 80 m from the trunk, but no pongamia seedlings were found beyond the single seedling at 22 m. Transect 3 extended along the wall of the restroom building. Along this wall, the transect was shady and moist due to a sprinkler system. Pods had probably fallen onto the roof and dropped off along the building wall, where some had germinated successfully in the moist shade. (maximum density 7 m^{-2}), however, where transect 3 extended beyond the building wall into sunnier, open areas of the garden, no pongamia seedlings were seen (Figure 23). Additional observations were made in areas adjacent to the H1 freeway, by looking through the garden wall and fence. This area along the H1 freeway was partially beneath the pongamia canopy. Vegetation consisted of weedy grasses, mainly finger grass (*Chloris barbata*) and buffel grass (*Cenchrus ciliaris*) mixed with herbs such as lilac tasselflower (*Emilia sonchifolia*), tridax daisy (*Tridax procumbens*), and obscure morning glory (*Ipomea obscura*). These plants are indicative of a dry, disturbed environment immediately outside of the garden; no pongamia seedlings were seen in this vegetation.

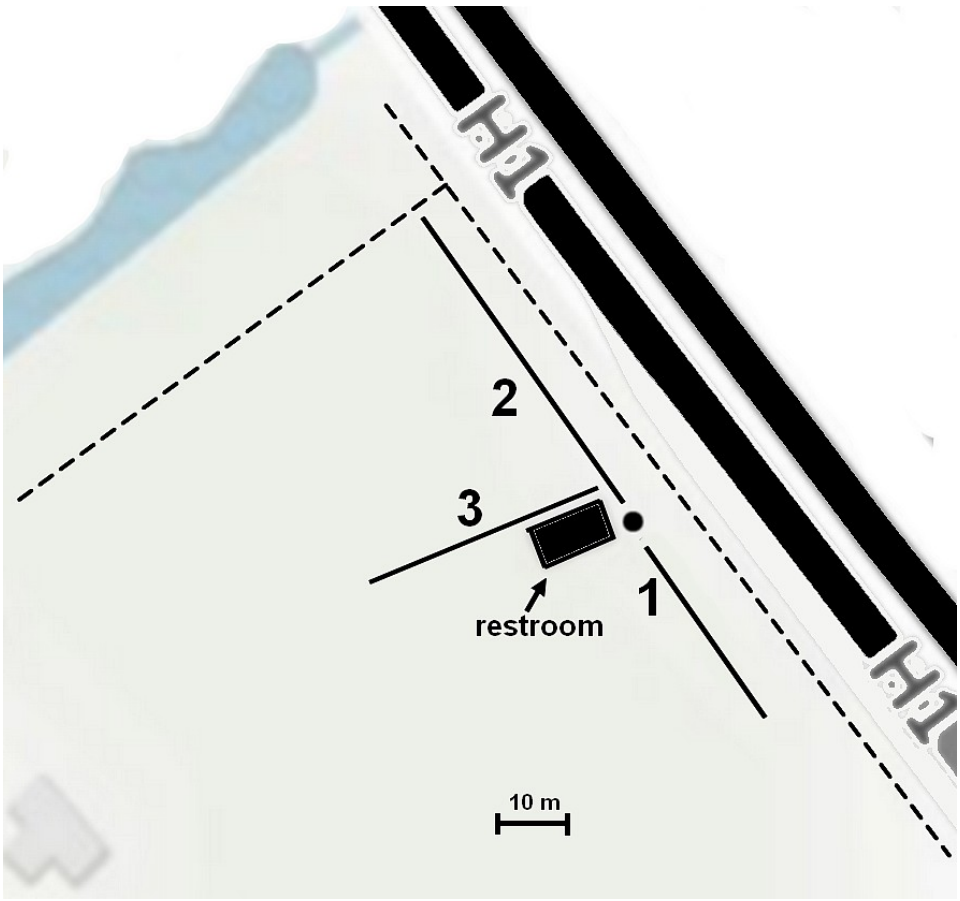

Figure 17. Location of the pongamia tree (solid circle) at Foster Botanical Garden. Dashed lines indicate a fence or wall. Solid thin lines indicate transects surveyed (transect width was 1 m). Thick lines indicate the H1 freeway.

Figure 18. The large trunk of the pongamia tree at Foster Botanical Garden. The restroom building is visible on the left side.

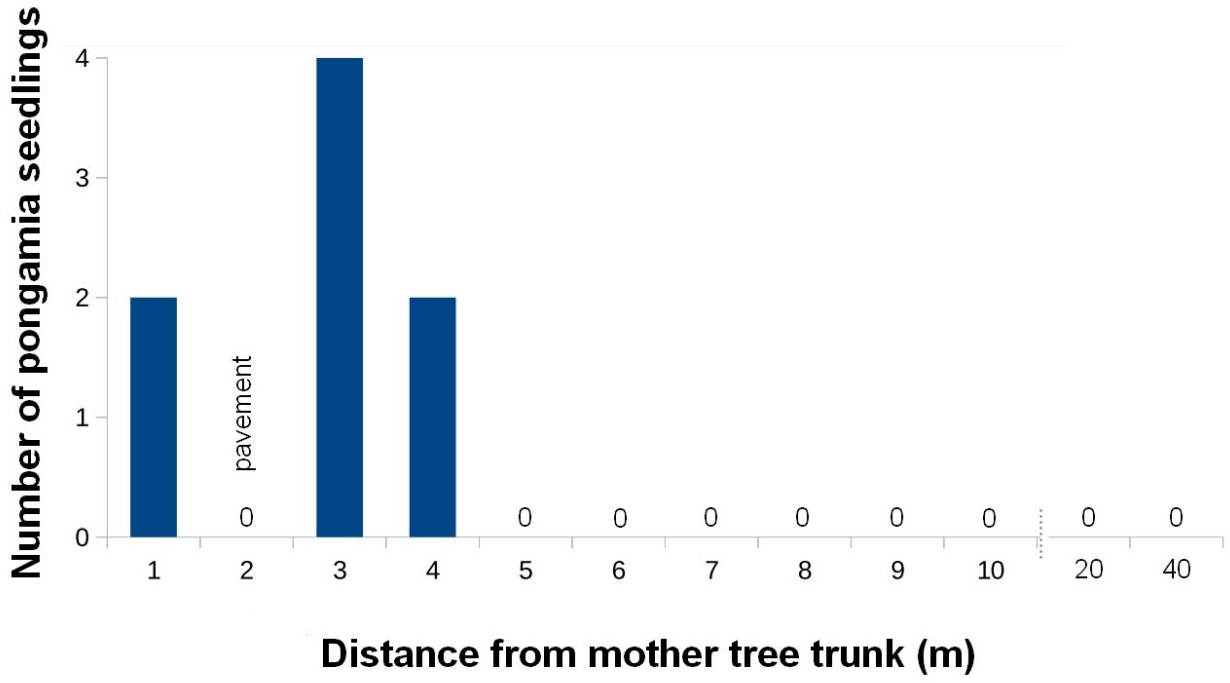

Figure 19. Pongamia seedlings found along transect 1 at Foster Botanical Garden. No root suckers were seen. Transect width was 1 m. Note the break in scale after 10 m. No pongamia seedlings were found between 11 and 40 m.

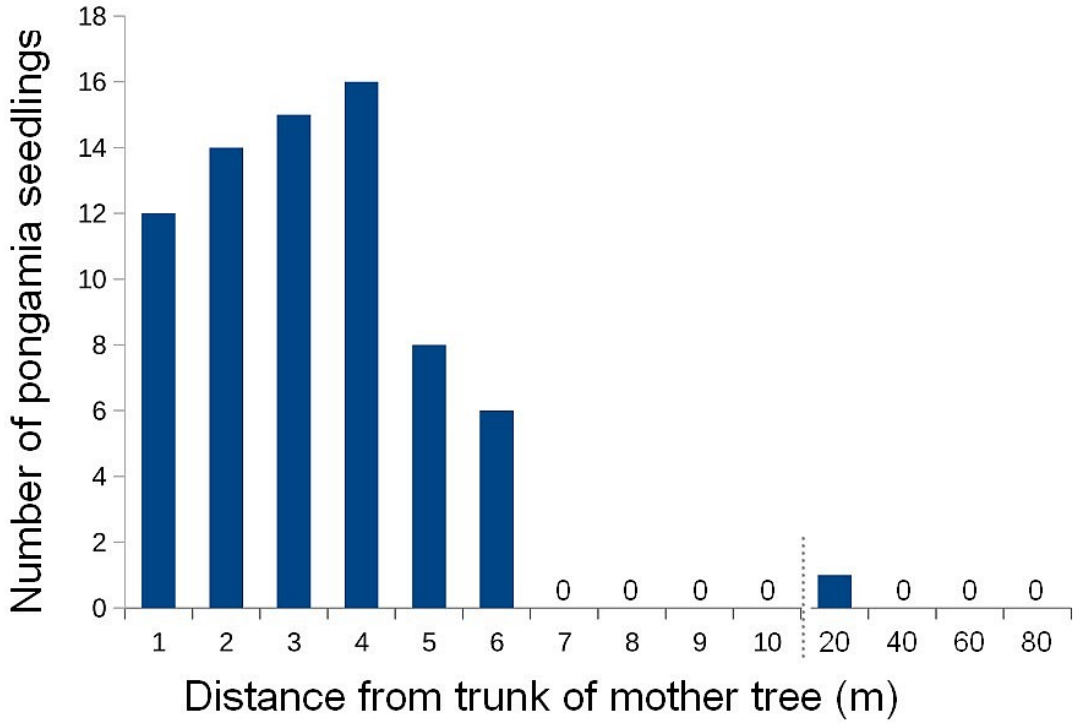

Figure 20. Pongamia seedlings found along transect 2 at Foster Botanical Garden. No root suckers were seen. Transect width was 1 m. Note the break in scale after 10 m. A single pongamia seedling was seen at 22 m, but no pongamia seedlings were found between 23 and 80 m.

Figure 21. Large-leaved pogamia seedlings seen on transect 2 (center) at Foster Botanical Garden, around 2 m from the trunk of the mother tree. The smaller-leaved plant at the left side, near the rock is a seedling of Fukian tea (*Carmona retusa*), a common weedy shrub.

Figure 22. This single pongamia seedling was found outside the canopy of the pongamia mother tree on transect 2 (22 m from the trunk) at Foster Botanical Garden. A seedling of the blue marble tree (*Elaeocarpus* sp.) is also visible in front of the larger-leaved pongamia.

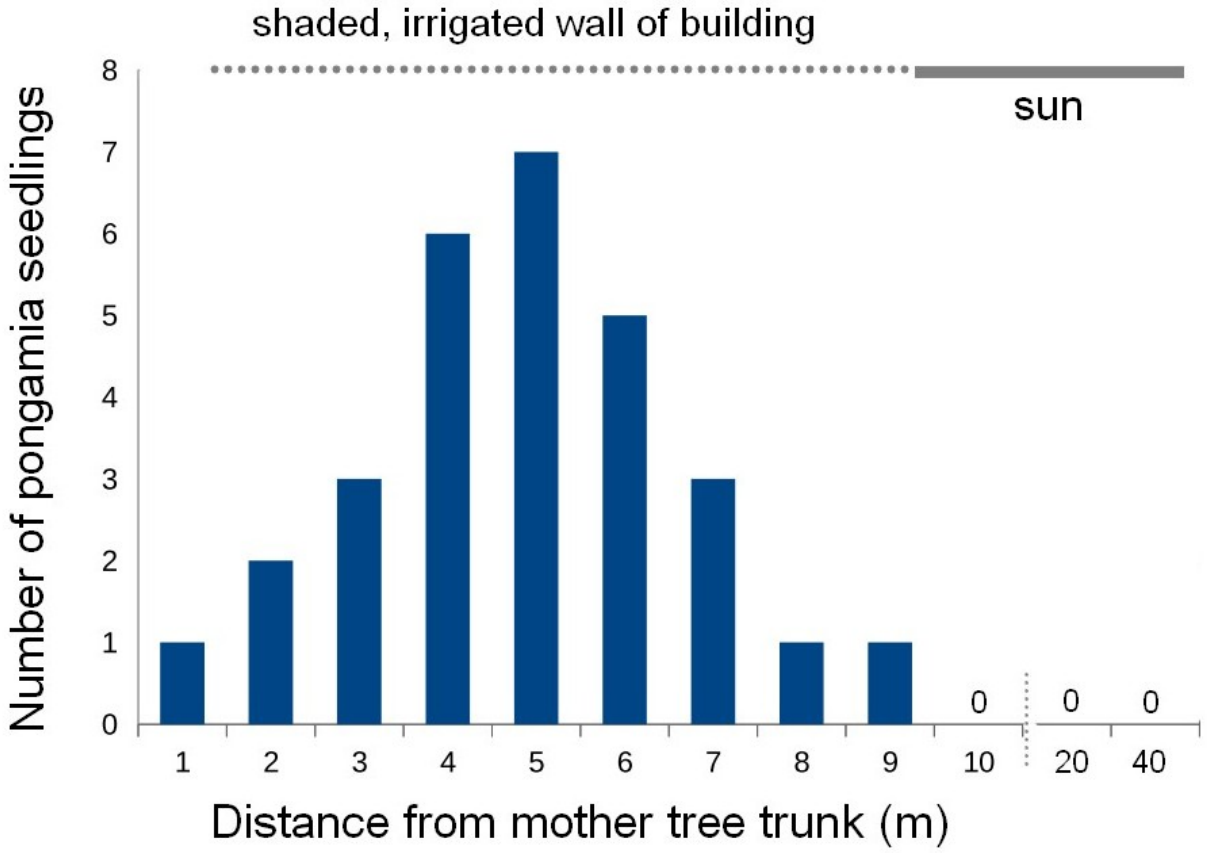

Figure 23. Pongamia seedlings found along transect 3 at Foster Botanical Garden. No root suckers were seen. Transect width was 1 m. Note the break in scale after 10 m. No pongamia seedlings were found between 11 and 40 m.

Waimea Valley, Haleiwa

A single large (~ 25 m) pongamia tree was observed at Waimea Valley (Figure 25). Five transects were established leading away from the tree in different directions as well as adjacent to the tree (Figure 24). Transect 1 straddled a short rock retaining wall; seedlings above and below the wall were counted along this 1 m wide transect. The most distant seedling along transect 1 was found 9 m from the trunk, while the pongamia canopy extended around 13 m along transect 1, therefore all observed seedlings were beneath the canopy (Figure 26, 27 and 28). Along transect 2, the pongamia canopy extended around 15 m and all observed seedlings were under the canopy (Figure 29). Transect 3 extended up a steep slope and into dense vegetation and was only followed for four meters; however, no seedlings were found beyond 1 m from the trunk along transect 3. No pongamia seedlings were observed along transects 4 and 5. The most common invasive plant along the Waimea Valley transects was roughplant (*Rivinis humulis*), indicative of a moderately wet, partially shaded environment.

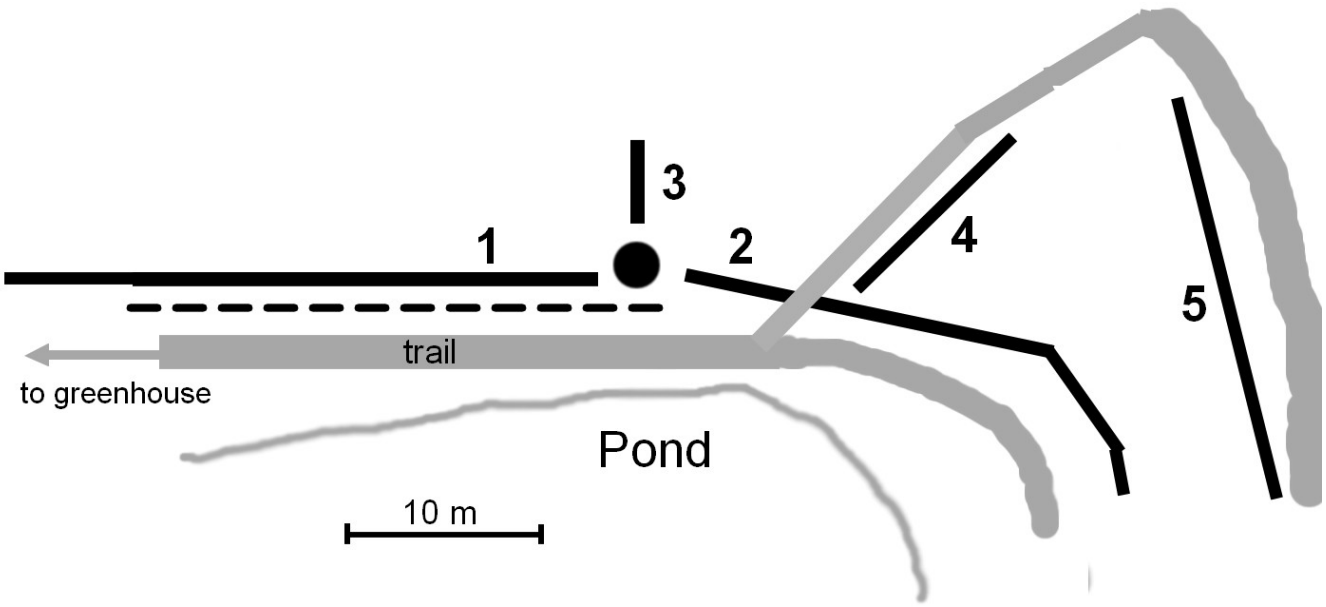

Figure 24. Map portraying the area around the pongamia tree (solid black circle) at Waimea Valley. The dashed line indicates a rock retaining wall (around 0.5 m high). Solid black lines indicate transects surveyed (transect width was 1 m).

Figure 25. The pongamia tree at Waimea Valley. Many leaves were yellowed.

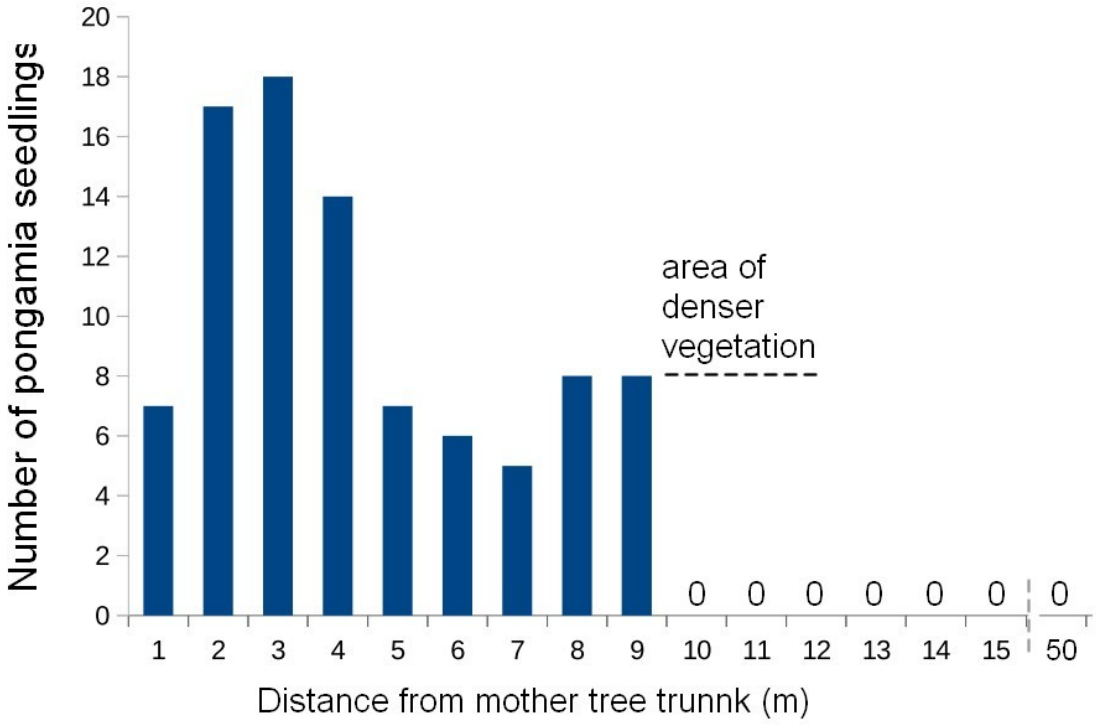

Figure 26. Pongamia seedlings found along transect 1 at Waimea Valley. No root suckers were seen. Transect width was 1 m. Note the break in scale after 15 m. No pongamia seedlings were found between 16 and 50 m.

Figure 27. Transect 1 at Waimea Valley, around 3 m from the trunk of the mother tree, showing the retaining wall along with pongamia seedlings and other plants growing on top of the retaining wall.

Figure 28. Transect 1 at Waimea Valley, around 3 m from the trunk of the mother tree, showing the retaining wall and pongamia seed pods and seedlings growing at the base of the retaining wall.

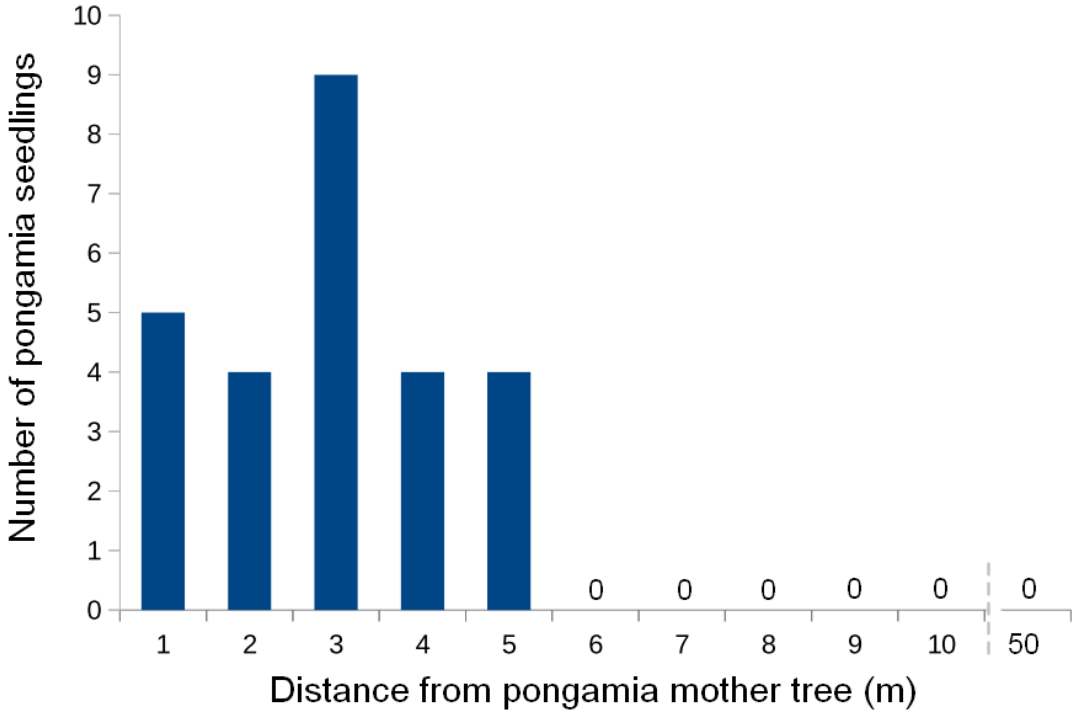

Figure 29. Pongamia seedlings found along transect 2 at Waimea Valley. No root suckers were seen. Transect width was 1 m. Note the break in scale after 10 m. No pongamia seedlings were found between 10 and 50 m.

Round Top Drive, Tantalus

A large (~15 m) pongamia tree was documented growing along the roadside of Round Top Drive in 1997 (Bishop Museum catalog number 690577, collected by Dr. G. J. Ray, formerly of the University of the Virgin Islands). A GPS location for the specimen was provided (21.3167, -157.817) along with a description of surrounding vegetation (*Montanoa hibiscifolia*, *Alocasia macrorrhiza*, and *Anredera cordifolia*). This site was visited (Figure 30) to determine if the pongamia tree survived and whether there was evidence of seedling recruitment (spread) from the mother tree. Upon exploring the vicinity of the original collection site, the tree apparently had died. A decaying trunk covered by an *Anredera cordifolia* vine was found (Figure 31). Because *Anredera cordifolia* is not common along Round Top Drive, and *Anredera cordifolia* was recorded growing near the pongamia in 1997, it is suspected that the decaying trunk may have been the pongamia documented by G.J. Ray in 1997. *Montanoa hibiscifolia* and *Alocasia macrorrhiza* were also found immediately adjacent to the *Anredera cordifolia*, matching the surrounding vegetation reported by G.J. Ray in 1997. Although the original pongamia tree no longer survives, the large tree would have dropped hundreds of thousands of seed pods over its lifespan. Therefore, the vicinity of the decaying trunk (presumed pongamia tree) was searched for evidence of pongamia seedling recruitment and spread. Transects were searched along the road and in vegetation around the dead tree (Figure 30). Around 400 m^2 were searched in total. No pongamia pods remnants were found, suggesting that the mother tree had died at least several years earlier, since even in the wet environment around Round Top Drive, pods would likely be identifiable for several years before completely decaying or being washed away. No pongamia plants were found. Seedlings, saplings and root suckers of various invasive woody plants were abundant along the transects (Figure 32). Common species included juniper berry (*Citharexylum caudatum*), octopus tree (*Schefflera actinophylla*), parasol leaf tree (*Macaranga tanarius*), Chinaberry (*Melia azedarach)*, and sumac (*Rhus taitensis)*. These invasive alien trees are indicative of a wet-mesic, disturbed environment.

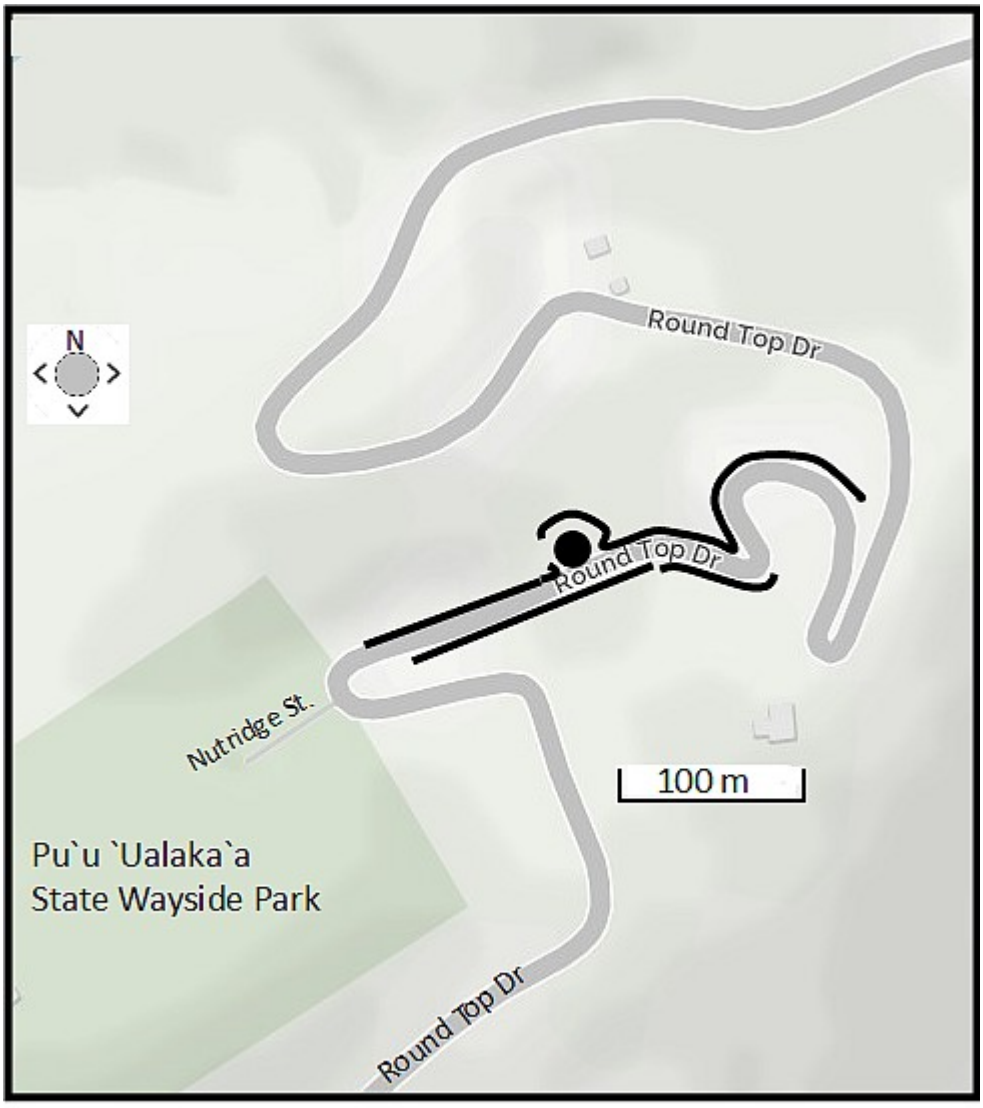

Figure 30. Map showing the presumed location of a dead pongamia tree (solid circle). Black lines indicate transects surveyed for pongamia seedlings.

Figure 31. The skeleton of a dead tree (presumed to be pongamia) together with a live *Rhus taitensis* tree are covered by the vine, *Anredera cordifolia* at the center of the photo. *Montanoa hibiscifolia* (a small tree /shrub) is also visible to the left, matching the original description of vegetation found at the site when the pongamia tree was known to be living in 1997. Roundtrop drive is visible at the right.

Figure 32 Disturbed vegetation with partially shaded, moist soil found in the vicinity of the dead tree presumed to be pongamia, near Round Top Drive. No pongamia seedlings, saplings or root suckers were found, although seedlings and root suckers of various invasive trees were found Juniper berry saplings are visible in this photo.

Discussion

Isolated pongamia trees on Oahu produced full-sized, viable seeds, confirming the ability of pongamia to produce viable self-pollinated seeds (Raju and Rao 2006). Field observations in the vicinity of seven known pongamia plantings on Oahu indicated that when pongamia is grown in dry environments such as Waipahu (HARC field station) and Ke'ehi Lagoon Beach Park, seeds are produced, but seedlings fail to establish naturally. The dry sites experience less than 800 mm of rainfall annually, with a summer dry season lasting for several months (Giambelluca et al 2013). Although no reports were found on minimum water requirements for pongamia seedling establishment, pongamia seedlings are adapted to survive in waterlogged soils (Arpiwi et al. 2013), and young pongamia seedlings seem to require relatively moist conditions for survival. On Oahu, pongamia seedlings were found establishing in artificially irrigated environments (Foster Botanical Garden and University of Hawaii Manoa campus), as well as under non-irrigated conditions at the wettest survey site (Waimea Valley; around 1200 mm annual rainfall). In these wetter conditions, seedlings were always found in shaded or partially shaded environments. This finding may reflect sensitivity of pongamia seedlings to water and / or heat stress, or an inability of pongamia seedlings to compete with fast-growing weeds that were abundant in sunnier areas within wetter environments. It is uncertain why seedlings larger than ~ 25 cm were not found at the moist and partially shaded sites, as even the largest seedlings at these sites appeared to be health. It is possible that maintenance staff remove or cut back larger seedling at these sites. It is also common for many tropical forest trees to maintain a "seedling bank" in shaded environments, where such seedlings will remain small until the opening of a light gap (e.g. due to death of an overhead tree).

In addition to apparent limitation of pongamia seedling recruitment to relatively moist and shady sites on Oahu, almost all pongamia seedlings were found immediately beneath the canopy of pongamia mother trees. This finding suggests lack of an effective dispersal method for pongamia seeds. Pongamia seed pods are naturally water dispersed (Nakanishi 1989). They can float and disperse via tides or nearshore ocean currents (Nakanishi 1989). Pongamia is also commonly found along riverbanks and streambanks in its native range (India Biodiversity Portal, accessed May 2018), indicating that seeds can be effectively dispersed by freshwater. Freshwater dispersal of pods or seeds seems unlikely in the vicinity of pongamia plantings on Oahu due to planting on relatively flat ground with no flowing water in the vicinity of the plantings. A stagnant pond was located within 15 m of the pongamia planting at Waimea Valley (Figure 24), but no ponagamia seedlings were found within the dense, grassy vegetation around the pond's edge, possibly due to competition from the weedy vegetation around the pond. The Round Top Drive site could have allowed for water dispersal due to steep slopes and high rainfall (1900 mm), but no pongamia seedlings were observed along Round Top Drive. No evidence of pod predation by rats or other vertebrates (potential seed dispersers) was found at any site. The lack of an effective dispersal mechanism in the vicinity of pongamia plantings on Oahu (with the exception of heavy rainfall along steep slopes on Round Top Drive, where the mother tree no longer survives) seems to limit pongamia seedling establishment to areas immediately beneath the canopy of mother trees. Rare pongamia seedling establishment beyond the canopy of the mother tree could have been due to high human foot traffic, which might incidentally disperse some pods (Foster Botanical Garden) or incidental short-distance transport by landscaping equipment (leaf blowers, mowers, etc; UH Manoa Campus).

Spread of pongamia by seed may also be limited by short seed longevity. While many plants in the family Fabaceae have a hard seed coat that allows ungerminated seeds to remain viable in the natural environment for years or even decades, pongamia seeds have a papery-thin seed coat (Figure 33). This thin seed coat will not provide longterm protection against desiccation or soil pathogens /

decomposers, and ungerminated seeds will likely become non-viable within a year. Manonmani et al (1996) reported reductions in viability after 3 months of storage. It may be possible to store pongamia seeds for longer periods under controlled laboratory conditions (e.g. Athaya 1985), but pongamia's lack of a persistent seedbank in the natural environment will reduce opportunities for seedling establishment outside of planting areas.

Figure 33. A mature pongamia seed showing the papery brown seed coat that can be easily peeled away using one's fingers, exposing the yellowish colored, tender cotyledons.

While many serious invasive plants spread via their seeds, it is also possible for plants to become weedy due to vegetative spread. Established pongamia trees have been reported to produce profuse root suckers (Food and Agriculture Organization of the United Nations Ecocrop Database, accessed May 2018), creating localized weed problems. No pongamia root suckers were observed on Oahu. Plantings at HARC and the North Shore may have been too young to exhibit root suckers; however, the remaining five sites visited had older trees. It is not clear why root suckers were not found at these sites. Most root suckers would be expected to be confined to the vicinity of 0-20 m from mother trees.

Conclusions and Recommendations

Based on its current behavior in the field, pongamia is not invasive or established outside of cultivation on Oahu. Although some pongamia seedlings were found in the vicinity of pongamia plantings on Oahu, 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 plantings. Pongamia pods and seeds are known to be water dispersed. Risks of pongamia escaping from a planting site could be substantially reduced by avoiding planting on steep slopes or in the vicinity of flowing water or ocean tides. A similar recommendation to avoid planting pongamia near river or stream banks was made by Kazakoff et al. 2011. In Hawaii, brief, heavy rainstorms may create temporary flowing water that could carry pods substantial distances, for example along sloped roadsides, or down a hill into a neighboring gulch. Potential water dispersal scenarios should be considered, and planting at sites that minimize the opportunity for water dispersal will reduce risks of pongamia escaping from plantings. Risk of pongamia spread by seeds can also be reduced through the secure transport of harvested seeds and pods during their transfer to processing sites. Unwanted vegetative spread of pongamia via root suckers has been reported at some planting sites outside of Hawaii. No root suckers were observed on Oahu; however, as plants age in plantation settings, pongamia root suckers might become a concern that could require active control at the edge of plantations as well as within plantations.

Acknowledgments

William Kusch, David Harry, and Elisabeth Beagle facilitated access to TerViva plantings on Oahu and provided background information on these plantings. This work was conducted with funding from the US Federal Aviation Administration (FAA) Office of Environment and Energy as a part of ASCENT Project 01 under FAA Award Number: 13-C-AJFE-UH, managed by James Hileman and Nathan Brown. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA or other ASCENT Sponsors.

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