Biology and Impacts of Pacific Islands Invasive Species: *Falcataria falcata* (Miquel) Barneby and Grimes (Fabaceae)[1]

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Abstract: *Falcataria falcata*, until recently known as *Falcataria moluccana* and commonly known as albizia, is a large, fast-growing tree native to the Malaysian peninsula, Indonesia, Papua New Guinea, and Solomon Islands. It has been introduced to, and become naturalized in, continental Africa, Asia, and many Caribbean and Pacific Islands. *F. falcata* is an early successional pioneer species that typically establishes via purposeful plantings. It readily spreads and outcompetes other tree species as a function of its symbiotic nitrogen-fixing capacity, copious long-lived seedbanks, and rapid growth rates. Due to their large stature at maturity (>30 m in height) and unstable architecture, *F. falcata* stands have the capacity to substantively alter the composition, structure, and function of lowland wet forests, and they pose a potent threat to both native forests and human communities across the Pacific. Despite negative aspects associated with its invasion, *F. falcata* has been harnessed for commercial profit and to increase soil fertility, particularly in its native range. *F. falcata* can be a component of productive agroforestry systems; the wood is used for firewood, as energy for industry, and timber in light construction. The nutrient-rich biomass of the tree is also used as mulch to increase crop production. However, given that mature stands were primarily responsible for millions of dollars of damage resulting from catastrophic tree fall during Tropical Storm Iselle on Hawai'i Island, and the potential interactions with climate change and development, managing this tree for its benefits as well as expanding research for its control is warranted.

Keywords: agroforestry, *Albizia*, *Falcataria moluccana*, Fabaceae, forest management, Hawai'i, invasive tree, *Metrosideros polymorpha*, nitrogen fixation, Pacific Islands

Falcataria falcata (Miquel) Barneby and Grimes (Fabaceae), until recently known as *Falcataria moluccana* (Wagner et al. 1999), is a fast-growing tree native to the eastern islands of the Malaysian peninsula, Indonesia, Papua New Guinea, and the Solomon Islands

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(Rojas-Sandoval 2023). In its native range, *F. falcata* is a post-disturbance, light-gap loving, early pioneer tree species (Parrotta 1990, Wagner et al. 1999). Where it has been introduced outside of its native range, large mature individuals often dominate forest canopies to the exclusion of native tree species. Its introduced range includes portions of continental Africa, Asia, and many Pacific Islands (PIER 2014, Rojas-Sandoval 2023). As one of the world's fastest growing large-stature trees, *F. falcata* has the potential to displace natural forests, devalue agricultural and residential areas, and damage energy and transportation infrastructure where it invades (Hughes et al. 2012). On Pacific Islands where it is acknowledged as a notable pest, *F. falcata* typically establishes via purposeful plantings from which it spreads as a function of physical and physiological attributes that enable it to grow rapidly and outcompete other trees (Parrotta 1990). Much of the altered ecosystem function and biodiversity loss engendered by *F. falcata* is due to its symbiotic nitrogen-fixing capacity that increases soil nitrogen availability and often destabilizes invaded ecosystems (Allison et al. 2006). High growth rates, voluminous stature at maturity (i.e., >30 m in height), and unstable architecture of *F. falcata* combine to pose an imminent threat to housing, transportation, and energy infrastructure via catastrophic tree and branch fall (Hughes et al. 2012).

A variety of management techniques have been utilized to control populations of *F. falcata* within its introduced range, and both physical and chemical management techniques have met with success, particularly those that exploit the species' particular vulnerabilities (e.g., shade intolerance) (Hughes et al. 2012, Hughes et al. 2013). At present, potential biological control agents for *F. falcata* are being identified, investigated, and tested (Bitume 2021).

Here we summarize chief attributes of *F. falcata* that make it a successful invader, the ecological and social impacts of its invasion, and current and future management techniques to control the spread and impact of the tree. Although its non-native range includes many tropical and subtropical areas of the world (Rojas-Sandoval 2023), we primarily focus on distribution and impact of *F. falcata* within the Pacific Basin and islands contained therein, with particular attention to the Hawaiian Archipelago.

TAXONOMY AND NOMENCLATURE

Phylum Angiospermae, Class Magnoliopsida, Order Fabales, Family Fabaceae, Subfamily Mimosoideae, Genus *Falcataria*, Species *Falcataria falcata* (L.) Greuter & R. Rankin.

Taxonomy of this genus has been mercurial; *Falcataria* has been classified and assigned with a variety of scientific names in the recent past, including reclassification from genera *Albizia* and *Paraserianthes* (Rojas-Sandoval 2023). Although known in contemporary literature as *Falcataria moluccana*, the current accepted name is *Falcataria falcata* (L.) Greuter & R. Rankin, with 12 synonyms (POWO 2023). *Falcataria* derives from the Latin word 'falcata', meaning "curved like a sickle," in reference to the plant's leaflets. *F. falcata* is known by more than 50 common names, which vary by geography (Table 1). In Cuba, the tree is known as both "albizia" and "peacock's plume"; in Hawai'i it is commonly referred to as "albizia." In Indonesia, it is referred to as "sengon" as well as a variety of other common names. The preferred common names for international usage are "albizia" or "batai wood" (Rojas-Sandoval 2023).

Synonyms: *Adenanthera falcata* L., *Adenanthera falcataria* L., *Albizia eymae* Fosberg, *Albizia falcata* (L.) Backer, *Albizia falcataria* (L.) Fosberg, *Albizia fulva* C.T. White & W.D.Francis ex Lane-Poole, *Albizia moluccana* Miq., *Falcataria moluccana* (Miq.) Barneby & J.W.Grimes, *Paraserianthes falcataria* (L.) I.C.Nielsen, *Paraserianthes falcataria* subsp. *fulva* (Lane-Poole) I.C. Nielsen, *Paraserianthes falcataria* subsp. *solomonensis* I.C.Nielsen, *Pithecellobium falcatum* (L.) Kosterm.

DESCRIPTION AND VARIATION

Species Description

Falcataria falcata is a broad-leaved perennial tree. Mature trees are classified as medium

TABLE 1

Common Names Used for *Falcataria falcata* in Various Regions Throughout the World

Location	Common Name(s)
Brunel Darussalam	puah, white albizia
Bangladesh	loroi, malacarma
Cook Islands	‘arapitia
Cuba	Albizia
Indonesia	albesia-wood, bae (Papua), bai (Papua), belalu, jeungjing, jeungjing sengon, mara, parasiante, rare (Maluku), seka (Maluku), selawaku merah (Maluku), selawoku (Maluku), sengon, sengon laut (Java), sika (Java), sika (Maluku), sika bot (Maluku), sikas (Maluku), tawa sela (Maluku), tedehu pute (Sulawesi), wahogon (Papua), wai (Papua), wikkie (Papua)
International (English)	albizia, batai, bataiwood, Indonesian albizia, kerosene plant, moluca, Molucca albizia, Moluccan albizia, Moluccan sau, paraserianthes, peacock plume, white albizia, white monkeypod
International (Spanish)	Albizia
International (French)	albizia, falcata
International (Chinese)	nan yang ying
Malaysia	batai, bataiwoo, kayu machis (Sarawak), Molucca albizia, Moluccan sau
Palau	ukall, ra, ngebard
Philippines	falcate, Mollucan sau
Portugal	albízia, bataí, mara, parasiante
Samoa	tamaligi, tamaligi pa’epa’e, tamaligi palagi
USA (Hawai‘i)	peacock’s plume

Source: Rojas-Sandoval (2023).

sized, but often attain diameters at breast height ≥100 cm and heights up to 40 m (Hughes, unpublished data, Wagner et al. 1999, Rojas-Sandoval 2023). Trees form large, umbrella-shaped canopies above straight, cylindrical trunks; bark is light gray, white, or greenish in color and smooth or slightly warty in texture (Wagner et al. 1999, Rojas-Sandoval 2023). Leaves are alternate, bipinnately compound, and dull green in color (Rojas-Sandoval 2023). Leaves generally exhibit 8–15 pairs of pinnae that contain 15–26 leaflets per pinna. Leaflets are falcate shaped (i.e., hook shaped), 10–20 mm long, and 3–6 mm wide (Wagner et al. 1999). Leaves possess a relatively large nectary located just below the lowermost pair of pinnae, and smaller nectaries may also be located at the juncture of the other pinnae pairs. *F. falcata* produces large, cream-colored, bell-shaped flowers in panicles, often with two serial branches, that are 13–25 cm long and 12–22 cm wide. The calyx is 1–1.5 mm long, with some pubescence and teeth; the corolla is cream to greenish yellow and 3–4.5 mm long, excluding stamens (Wagner et al. 1999, Rojas-Sandoval 2023, Wagner and Khan 2023). Fruits typically contain 15–20 seeds and are narrow (i.e., 1.5–2.5 cm), relatively long (i.e., 9–12 cm), glabrous, and brown in color (Wagner et al. 1999). As fruits dry, they typically split in half lengthwise, with each half retaining an equal number of seeds; these fruit halves constitute the windborne, multi-seeded dispersal units of *F. falcata* (Figure 1). Seeds are ellipsoid, dark brown, 5 7 mm long, 2.5 3.5 mm wide, laterally flattened with a pleurogram ca. 3 mm long and 1.5 mm wide, and winged (Rojas-Sandoval 2023, Wagner and Khan 2023) (Figure 1).

Distinguishing Features

F. falcata may be confused with *Albizia chinensis* (Osbeck) Merr. (a.k.a., Chinese albizia or chocolate albizia) which occurs within the non-native range of *F. falcata* in Hawai‘i and elsewhere (Wagner et al. 1999, Pasiecznik

FIGURE 1. *Falcataria falcata* plants and plant parts, clockwise from upper left: young leaves, flowers, fruits, fruits on tree, and an *F. falcata*-invaded field. Photo credit: Joanna Norton.

2014). A former congener of *F. falcata*, *A. chinensis* exhibits superficial similarities but generally exhibits comparatively shorter canopies (i.e., heights up to 20–30 m), is often multi-stemmed, and expresses bark that is dark-gray and smooth (Zabala 1997, Wagner et al. 1999, Pasiecznik 2014, PIER 2014). Leaflets of *A. chinensis* are somewhat smaller (i.e., 6–10 mm long and 2–3 mm wide) and exhibit an acute apex in contrast to the falcate (hooked) appearance of *F. falcata* leaflets. New leaves of *A. chinensis* are typically rust-red, which distinguishes the species from *F. falcata*. Both *F. falcata* and *A. chinensis* exhibit whitish flowers borne on terminal panicles, but flowers of *A. chinensis* are larger than those of *F. falcata* (i.e., 8–12 mm in length compared to 1–1.15 mm in length) (Wagner et al. 1999, PIER 2014, Pasiecznik 2014, Rojas-Sandoval 2023). Fruits of *A. chinensis* contain 8–12 seeds, are glossy, flat, and thin. They are somewhat longer and wider (i.e., 3.5 cm wide) than seed pods of *F. falcata* (i.e., to 2.5 cm wide) which are densely pubescent and bear 15–20 seeds (Wagner et al. 1999, Krisnawati et al. 2011, Pasiecznik 2014). Regarding climate, *F. falcata* and *A. chinensis* occupy similar environments, but *A. chinensis* is not invasive to the degree that *F. falcata* is.

Intraspecific Variation

Progeny studies in its native habitat to examine genetics, survival, and disease resistance found that *F. falcata* exhibits considerable natural intraspecific variation that could be useful for artificial selection (Baskorowati et al. 2017). In 23-year old plantation settings in Okinawa, Japan (introduced range), trees exhibited a 3.6-fold variation in diameter at breast height (DBH), and a 2.6-fold variation in height (Kawai et al. 2023). Variable traits

among individual trees included leaflet area, inner wood water content, and inner and total bark thickness (Kawai et al. 2023). However, other leaflet-level traits did not differ among individual trees (i.e., leaflet mass per area, leaflet N concentration, leaflet $\delta^{13}C$) and were independent of tree size. Wood traits (e.g., inner and outer wood density) were variable with tree size (Kawai et al. 2023). In Hawai'i, individual growth of 20-year-old trees depended on interactive effects among relative tree size of *F. falcata* and *Eucalyptus saligna*, and soil N and P levels (Boydon et al. 2005). Studies indicated that *F. falcata* traits varied with respect to environmental conditions, tree size, and interspecific competition.

HISTORY OF INTRODUCTION AND INVASION

Spread of *F. falcata* from its native range to various Pacific Islands landscapes was the result of purposeful plantings and subsequent seed dispersal from planted individuals (Woodcock 2003, Motooka et al. 2011); the species was often planted for reforestation purposes to help stabilize soils (Meyer 2007). Where introduced, *F. falcata* often quickly naturalized, leading to ecological and economic impacts across landscapes (Hughes and Denslow 2005, Meyer 2007). Regarding Hawai'i specifically, the first *F. falcata* individuals were collected from Borneo and Java and introduced to the island of O'ahu by the eminent botanist, Joseph Rock in 1917. From Rock (1920):

> This species, commonly known as Albizia moluccana, was introduced by the writer [i.e., Rock] from British Borneo and Java in 1917. Hundreds of seedlings were grown and planted out by the Board of Agriculture and Forestry [of Hawaii]. Specimens have been set out on the College of Hawaii grounds, where they are doing splendidly. This species, a native of the Moluccas, reaches a height of over 120 feet during a period of less than 25 years, about its life period. Experiments carried on at the Gardens in Java showed that trees 2 years and 9 months old had reached a height of 56 feet, while trees nine years old had reached a height of over a hundred feet, a rapidity of growth almost unbelievable. In Hawaii the trees have not shown such a phenomenal rate of growth, though their growth has been very rapid in comparison with other trees. The trees have reached an average height of 15 to 18 feet in about a year's growth. The species likes heavy clay soil, and an abundant amount of moisture. It can be advocated for plantings in heavy soil as a soil improver. The enormous root system which the tree develops produces channels for the draining and airing of the soil. The great amount of green manure produced by the fallen leaves tends to further improve the soil. The only objection to the tree is its short-lived period, but as it is an abundant seeder there should always be a good stand of this tree present. (Figure 2)

Approximately 138,000 *F. falcata* trees were planted across the Hawaiian Archipelago during the 1900s as part of extensive non-native tree planting efforts led by Hawai'i Territorial Foresters concerned about native-forest degradation due to decades of deforestation, ungulate damage, and fire (Woodcock 2003). In addition to planted seedlings of *F. falcata*, seeds of the species were distributed from airplanes to establish populations throughout the Hawaiian Islands (Wagner et al. 1999); it is now naturalized on the main Hawaiian Islands of Hawai'i, Maui, Moloka'i, O'ahu, and Kaua'i. Similar practices in French Polynesia and other Pacific Islands resulted in the widespread establishment of *F. falcata* (Meyer 2007). In Samoa, individuals of the species were introduced to Upolu Island as early as the 1830s, and populations had spread to Tutuila Island by the early 1900s. The species was noted present in Samoa by Christophersen (1938) during the 1930s, and it was commonly found in villages of Pago Pago on Tutuila Island by the 1950s (Hughes et al. 2012). *F. falcata* continues to be planted in many parts of the world for lumber or as a shade/green manure source where local economics make tending the trees a viable labor choice (Zabala 1997).

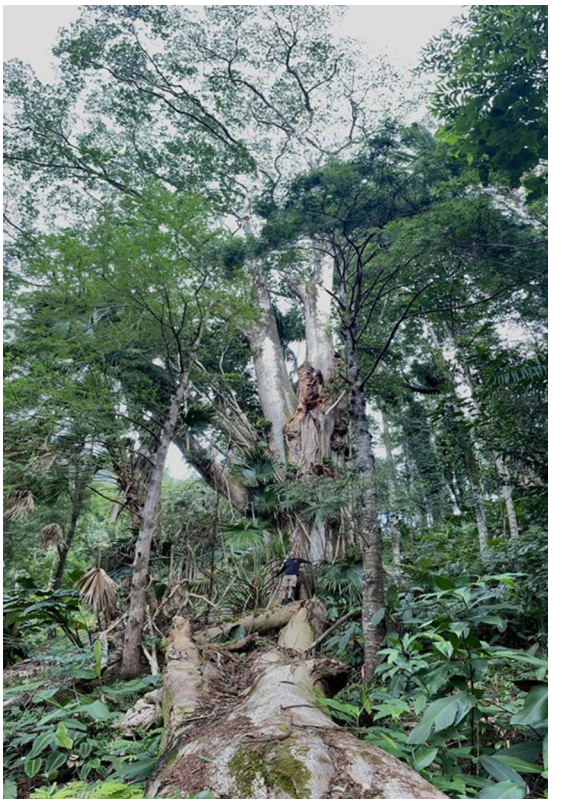

FIGURE 2. Photo taken in 2023 of a *Falcataria falcata* individual among the first planted by Joseph Rock in 1917 on grounds that are now occupied by Lyon Arboretum of the University of Hawai'i at Mānoa campus, O'ahu, Hawai'i. Photo credit: Chloe M. Hughes.

GEOGRAPHIC DISTRIBUTION

F. falcata is native to the Indonesian peninsula, the Molucca Islands, West Irian Jaya, Papua New Guinea, New Britain, and Solomon Islands (Rojas-Sandoval 2023). *F. falcata* has been distributed far beyond its native range and is considered an invasive species in portions of continental Africa, Asia, as well as many Pacific Islands (Table 2; Figure 3) (PIER 2014, Rojas-Sandoval 2023). Though introduced and naturalized in China and the Philippines, *F. falcata* is a species of commercial value in both nations (Nissen and Midmore 2002, Ji et al. 2017) and has not been designated as invasive in either (Rojas-Sandoval 2023). As with other invasive species, perceived impacts of *F. falcata* on native ecosystems, economics, or human welfare may vary greatly.

Habitat

F. falcata occurs in humid climate biomes (i.e., moist forests and rainforests). In its native range, *F. falcata* behaves as a fast-growing early successional pioneer species, flourishing in high light tree-fall gaps and larger areas disturbed by catastrophic storms or logging operations. Where it is introduced and naturalized, *F. falcata* can be found in lowland and sub-montane forests, plantations, pastures, as well as disturbed areas and floodplains (Little and Skolmen 1989, Starr et al. 2003, Rojas-Sandoval 2023).

Climatic Requirements

F. falcata individuals and stands typically occur in lowland areas below 1,500 m and at latitudes ranging from 10°S to 30°N (Rojas-

TABLE 2

Global Distribution of *F. falcata* with Focus Pacific Islands in Particular

	Present/Absent
Pacific Islands	
American Samoa	Present[a]
Australia	Absent[c]
Bonin Islands	Absent[c]
Cocos Islands	Absent[c]
Cook Islands	Present[a,b]
Easter Island	Present[a]
Fiji	Present[a,b]
French Polynesia	Present[a,b]
Galapagos Islands	Absent[c]
Guam	Present[a]
Hawaiian Islands	Present[a,b]
Indonesia	Present[a,b]
Japan	Present[b]
Juan Fernandez	Absent[c]
Kiribati	Absent[c]
Marshall Islands	Absent[c]
Micronesia	Present[a,b]
Nauru	Absent[c]
New Caledonia	Present[a,b]
New Zealand	Absent[c]
Niue	Present[a]
Norfolk Island	Present[b]
Northern Mariana Islands	Absent[c]
Palau	Present[a]
Papua New Guinea	Present[a,b]
Philippines	Present[a,b]
Pitcairn Island	Absent[c]
Solomon Islands	Present[a,b]
Taiwan	Present[b]
Tokelau Island	Absent[c]
Tonga	Present[a]
Tuvalu	Absent[c]
Vanuatu	Absent[c]
Wake Island	Absent[c]
Wallis and Futuna	Present[a,b]
Asia	
Bangladesh	Present[a]
China	Present[a,b]
India	Present[a]
Malaysia	Present[a,b]
Singapore	Present[a]
Sri Lanka	Present[a,b]
Taiwan	Present[b]
Africa	
Angola	Present[a]
Benin	Present[b]
Cameroon	Present[a,b]
Côte d'Ivoire	Present[a]
Guinea-Bissau	Present[a]
Kenya	Present[a]
Madagascar	Present[a,b]
Malawi	Present[a]
Mauritius	Present[a]
Mozambique	Present[a,b]
Nigeria	Present[a]
Réunion	Present[a,b]
Sao Tome & Principe	Present[a,b]
Seychelles	Present[a,b]
Togo	Present[b]
Uganda	Present[a]
Zimbabwe	Present[a]
South America	
Bolivia	Present[b]
Brazil	Present[b]
Ecuador	Present[b]
Peru	Present[b]
Venezuela	Present[a,b]
North America	
Cuba	Present[a]
Guadeloupe	Present[b]
Mexico	Present[a,b]

[a] Rojas-Sandoval (2023).
[b] Instances found on Global Biodiversity Information Facility (GBIF.org 2023).
[c] Presumed absent. Not mentioned in Rojas-Sandoval (2023).
Source: Rojas-Sandoval (2023) and The Global Biodiversity Information Facility (GBIF.org 2023).

Sandoval 2023) that exhibit mean annual temperatures from 22 °C to 34 °C (Soeria-negara and Lemmens 1993). Regarding Hawai'i specifically, *F. falcata* grows across broad environmental conditions from sea level to 600 m, on barren lava flows aged <50 years to well-weathered soils aged over 4 million years, on mesic to perudic sites, and on windward to leeward sides of the islands.

Soil Resource Requirements

As a member of the Fabaceae (legume family), a salient feature of *F. falcata* is its capacity to form a symbiotic relationship with rhizobia soil bacteria within its root system (Figure 4).

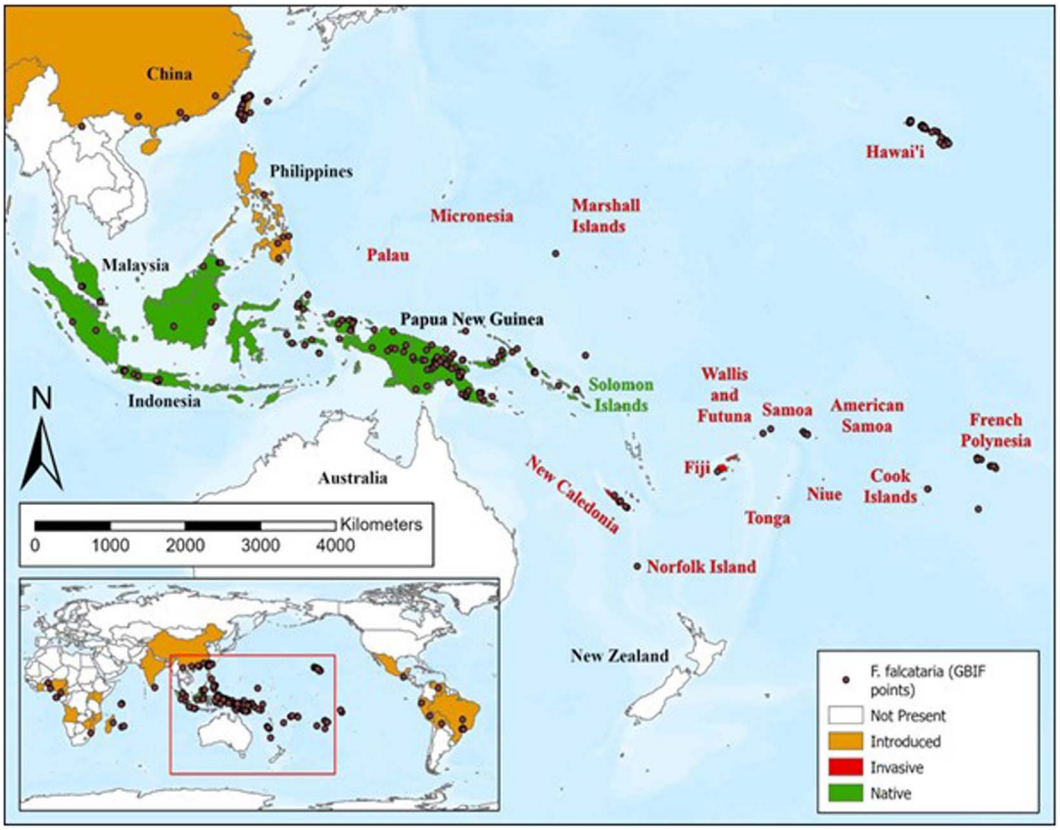

FIGURE 3. Global distribution of *Falcataria falcata* (bottom left inset) and its distribution across the Pacific Basin. Brown dots represent occurrence data (GBIF.org 2023), and color coding of status (introduced, invasive, or native) was based on Rojas-Sandoval (2023).

The bacteria absorb atmospheric dinitrogen (N_2), convert it to biologically-available ammonia (NH_3) via the nitrogenase protein complex, and provide it to the tree in exchange for fixed energy (i.e., organic carbon). This bacterial symbiosis releases *F. falcata* from constraints of soil available N limitation (Vitousek and Farrington 1997), and allows it to grow rapidly during primary succession on highly N-limited lava flows in Hawai'i (Hughes and Denslow 2005, Hughes et al. 2014) and sites exhibiting N-limited soils due to mining, or intensive agriculture (Garcia-Montiel and Binkley 1998, Otsamo 2000). Its symbiotic N-fixing capacity is among the reasons *F. falcata* is simultaneously a soil improver and a potent invader that ranks among the fastest growing trees in Hawai'i (Walters 1971). Indeed, *F. falcata* growth and productivity are more likely constrained by soil phosphorus availability than soil N supply (Binkley 1997, Binkley et al. 2003, Houlton et al. 2008, Kueffer 2010).

Light Requirements

An early successional pioneer species, *F. falcata* grows rapidly in high light environments (Hughes et al. 2014) and requires high levels of solar radiation to survive and grow. Seedlings are particularly sensitive to shade and germinate only where overstory canopies allow for sufficient light penetration (Soerianegara and Lemmens 1993). In lowland wet forests of Hawai'i Island, light levels as high as 20% of ambient failed to promote *F. falcata*

FIGURE 4. Close-up image of a *Falcataria falcata* seedling root system with associated *Rhizobium* bacteria structures attached to several roots. Photo credit: Kyson Dunn.

seed germination and growth, and saplings of the species were entirely absent beneath closed-canopy forests dominated by either *F. falcata* or the endemic tree, *Metrosideros polymorpha* (Hughes and Denslow 2005). Similarly, killing large invasive *F. falcata* individuals in forests of American Samoa did not result in reestablishment of new cohorts of seedlings and saplings because post-control germination of the extensive *F. falcata* seed bank was preempted by rapid growth and light suppression of surrounding native Samoan tree species (Hughes et al. 2012). Ideal light environments for *F. falcata* include young and sparsely vegetated lava flows, disturbed forests, and cleared land in and around residential developments, transportation corridors, and energy grid infrastructure (Hughes and Denslow, 2005, Hughes et al, 2013, Niemiec et al. 2018, Hughes et al. 2022). As such, in addition to displacing native forest species and altering ecosystem function, *F. falcata*'s proclivity to invade disturbed areas of built environments has made it a threat to life and property across many regions of the Hawaiian Islands and elsewhere in the Pacific (Butler 2014).

PHYSIOLOGY

Many physiological features of *F. falcata* contribute to its invasiveness. Recognized as among the world's fastest growing tree species, *F. falcata* can average a 2.5 cm gain in height per day (Walters 1971, Footman 2001), with associated high rates of aboveground net primary productivity manifesting as high C mass accumulation rates (Mascaro

et al. 2012, Hughes et al. 2014, Hughes et al. 2022) and high litterfall rates (Hughes and Denslow 2005). As an early succession pioneer species, *F. falcata*'s strategy to grow rapidly to attain overstory height necessitates high rates of carbon assimilation and commensurate high rates of water uptake and transpiration (Larcher 1980); its symbiotic N-fixing association with *Rhizobium* bacteria also increases C demand and concomitant water demand (Marschner 1995) as well as demand for soil phosphorus (Binkley 1997). Although *F. falcata* in its native range is purported to have a life span limited to several decades to 50 years (Rock 1920), in Hawai'i individuals have lived beyond 100 years (Hughes and Denslow 2005, Niemiec et al. 2018).

REPRODUCTION

Reproductive characteristics of *F. falcata* certainly contribute to its success as an invasive tree. Individuals reach reproductive maturity just 4 years after germination (Parrotta 1990), and annually produce large numbers of multi-seeded diaspores that can be wind-dispersed over substantial distances (i.e., >200 m up-slope and down-slope during windy conditions) (Little and Skolmen 1989, Hughes et al. 2013). Copious seed production also leads to development of large seed banks beneath canopies of mature trees that are poised to germinate when light availability becomes sufficient. Hughes (unpublished data) documented as many as 2,200 seedlings per square meter germinating from soils beneath well-established stands of mature *F. falcata* whose canopy and forest floor biomass had been removed. Currently, little is known about pollination systems of this species; research to examine both pollination systems and seed dispersal would help inform potential controls on population dynamics.

POPULATION DYNAMICS

Population dynamics of *F. falcata* are primarily determined by the light requirements of the species. Whether as seedlings, saplings, or mature adult trees, *F. falcata* individuals require abundant light and develop as an even-aged cohort stand whose individuals are strongly competitive for available solar radiation; where trees are overtopped and shaded by other *F. falcata* individuals or other plant species, they invariably perish. Mature individuals that have captured an area often coalesce to form multi-hectare canopies that may be >30 m in height. In Hawai'i as well as in American Samoa, mature *F. falcata* trees tend to be the tallest trees in any forest, effectively overtopping most if not all native trees. Because of that, and the fact that individuals of any age and size are unable to survive beneath overstory canopies, *F. falcata* individuals, stands, and forests are easily detectable using remote sensing approaches: individuals are either clearly present in the overstory canopy, or they are absent (Niemiec et al. 2018).

Further, the tall umbrella-shaped canopies of *F. falcata* often provide optimal habitat for many of Hawai'i's worst forest weeds such as *Psidium cattleyanum* (a.k.a. strawberry guava) and *Miconia crenata* (a.k.a. Koster's curse); these are species that can tolerate the intermediate levels of shade cast by *F. falcata* overstory and capitalize on increased soil nutrients provided year-round via litterfall produced by the highly productive trees (Hughes and Denslow 2005). In contrast, seedling, saplings, and mature individuals of Hawai'i's dominant native overstory tree, *Metrosideros polymorpha*, are unable to survive beneath the broad canopies of *F. falcata* (Hughes and Denslow 2005, Hughes et al. 2022). An invaded forest typically exhibits a dense sub-canopy of non-native understory weed species such as *P. cattleyanum*, *M. crenata*, *Melastoma septemnervium*, and/or *Setaria palmifolia* (Asner et al. 2008).

ECOLOGICAL IMPACT AND ECONOMIC IMPORTANCE

Detrimental Aspects

Detrimental impacts of *F. falcata* invasion are numerous and multi-faceted but can be broadly grouped into two main categories: compositional, structural, and functional alterations to native ecosystems and economic

impact on human populations (Figure 5). *F. falcata* decreases native biodiversity within its introduced range while also providing better habitat for other invasive species (Hughes and Denslow 2005). Additionally, *F. falcata* is known as an urban pest responsible for considerable damage to infrastructure (Hughes et al. 2012).

A hallmark of invasive, N-fixing tree species such as *F. falcata* is their capacity to alter ecosystem functions where they establish (Vitousek et al. 1987, Vitousek and Walker 1989) and facilitate invasion of other non-native species that would be otherwise excluded. *F. falcata*'s capacity to alter ecosystem functioning is made more pronounced by its high rates of productivity (Hughes and Denslow 2005), rapid growth (Walters 1971, Footman 2001), large stature at maturity with respect to individual canopy height and breadth, and the manner by which multiple adjacent individual trees coalesce to form contiguous "mega-canopies" (Hughes et al. 2014, Niemiec et al. 2018). These traits, in addition to its persistent seed bank, wind dispersal, responsiveness to disturbances, climate matching, and ability to tolerate variable soil conditions, collectively lead to a classification of "likely to become a pest" by the Hawai'i Pacific Weed Risk Assessment (Daehler et al. 2004, https://plantpono.org/high-risk-plants/).

Where *F. falcata* invaded native forest dominated by the Hawaiian endemic overstory tree, *M. polymorpha*, Hughes and Denslow (2005) documented nitrogen and

FIGURE 5. Landscapes illustrating *Falcataria falcata* invasion into native forests of Keau'ohana (upper left) and Mālama Ki (upper right) Forest Reserves, Hawai'i Island as well as residential areas of the Puna district, Hawai'i Island (lower left and right). In all cases, *F. falcata* manifests as large globular single canopy trees or contiguous closed-canopy overstories. Photo credit: R. Flint Hughes.

phosphorus inputs from annual litterfall rates as high as 243 kg ha^{-1} yr^{-1} and 8.9 kg ha^{-1} yr^{-1}, respectively. Such rates were 55× and 28× greater, respectively, than comparable sites dominated by *M. polymorpha* stands and translated to available soil N and P values that were as much as 121 times and 24 times greater, respectively, in *F. falcata*-dominated forests relative to *M. polymorpha*-dominated forest counterparts (Hughes and Denslow 2005). Hughes and Denslow (2005) also found that increased nutrient inputs—particularly nitrogen—driven by *F. falcata* stand development during primary succession on very young lava flows (i.e., <50 years old)—facilitated invasion by what has become Hawai'i's most abundant non-native tree, *Psidium cattleyanum* (Owen et al. 2021), which would otherwise be excluded from such N-limited substrates without increased N inputs from *F. falcata*. In contrast, *M. polymorpha*, whose even-aged stands typically dominate early to middle stages of primary succession on Hawai'i's young lava flows (Atkinson 1970, Mueller-Dombois and Fosberg 1998, Hughes et al. 2022), was excluded from young lava flows invaded by *F. falcata* (Hughes and Denslow 2005). Similarly, where populations of *M. polymorpha* established and developed immediately following the clearcutting of mature lowland wet forests in Hawai'i, those second-growth forests remained dominated by *M. polymorpha* and free of *F. falcata* after nearly three decades of secondary succession. However, in areas of the same clearcut region that were invaded by *F. falcata* during early stages of secondary succession, *M. polymorpha* individuals were effectively excluded from those second-growth forests (Hughes et al. 2022). These patterns of primary and secondary succession within Hawai'i's lowland wet forests illustrate how *F. falcata* stands, by altering soil nutrient and light availability, induce an "invasional meltdown" that severely reduces native species' populations and facilitates subsequent invasion by other non-native species (Hughes and Denslow 2005).

Increased soil nitrogen availability within *F. falcata* forest stands also results in changes to both soil microbial communities and their biogeochemical processes. Allison et al. (2006) found that *F. falcata* invasion altered microbial community composition and the production of extracellular enzymes, particularly phosphatase. Such changes were likely driven by large increases in litter quantity and N concentration under *F. falcata*-dominated forest stands compared to nearby native-dominated forest, and most certainly facilitated positive feedbacks to nutrient cycling in *Falcataria*-invaded stands. Indeed, Hughes and Uowolo (2006) found that *F. falcata* invasion increased rates of decomposition well above those of the native-dominated forest stands they replaced. They also demonstrated that increased decomposition rates were driven by sustained stand-scale increases in nutrient inputs via litterfall and coincidental changes in soil biota associated with *F. falcata* invasion (Hughes and Uowolo 2006). Similarly, Tuttle et al. (2009) found that *F. falcata* invasion, by providing ideal habitat through deposition of nutrient-rich leaf litter, increased abundance of non-native shredding invertebrates (i.e., Amphipoda and Isopoda) by 400% and increased non-native predaceous ants (Hymenoptera: Formicidae) by 200% relative to adjacent native forest stands. Further, soil emissions of nitrous oxide (N_2O) and nitric oxide (NO)—both significant air pollutants—were higher beneath *F. falcata*-dominated stands compared to adjacent native *M. polymorpha* stands (Hall et al. 2018).

Increased nitrogen levels in soils surrounding *F. falcata* also decreased water quality of nearby streams (Wiegner et al. 2013). Streams along windward slopes of Hawai'i Island exhibited concentrations of nitrate and nitrite from water sampled below mature *F. falcata* stands that exceeded Hawai'i Department of Health's dry season standards for those potential pollutants; such increases in dissolved N levels released algae from N limitation and drastically altered stream chemistry (Wiegner et al. 2013).

F. falcata is also a roadside, urban forest, and residential pest of significance. The economic impacts of *F. falcata* are due primarily to tree falls, as its architecture makes it prone to branch and limb failure, particularly under high wind conditions and storm events (Hughes et al. 2012). The potential economic

burden posed by *F. falcata* can be stunning. In the state of Hawai'i, it has been estimated that *F. falcata* accounts for over 40% of all infrastructure damage caused by tree falls (Hughes et al. 2013). In 2009 on the island of Kaua'i, the Hawai'i Department of Transportation (HDOT) spent one million dollars to remove *F. falcata* individuals growing along a single mile of roadway; arborists were forced to employ expensive cranes and lifts, and safe removal of larger trees cost more than $10,000 per individual (Watson 2018). In another example, on the University of Hawai'i at Hilo campus where multiple *F. falcata* stands threaten classrooms, dormitories, ballfields, and parking lots, removal of a single large tree cost $5,000 in 2023 (William Walters, personal communication). Where *F. falcata* stands grow in riparian zones, trunks and large branches may fall into waterways and accumulate against bridges, potentially causing flooding and physical damage to critical infrastructure. Dangers presented by *F. falcata* individuals and stands became apparent during Tropical Storm Iselle in 2014, which made landfall in Hawai'i Island's Puna district. Most of the hazards and damage were due to falling *F. falcata* trees, which accounted for approximately 90% of immediate costs from the storm (Albizia Project Committee 2015), and residents in multiple neighborhoods were trapped for days as workers and local volunteers cut through fallen trunks to clear roadways (Figure 6). Damages in the immediate aftermath topped $20 million dollars, and, after all major FEMA and HELCO claims, damages totaled $45 million or more in the Puna district of Hawai'i Island (Albizia Project Committee 2015).

Beneficial Aspects

In some parts of the world, the high growth rates and N-fixing capacity exhibited by *F. falcata* trees and stands have been harnessed to increase forest productivity, commercial profit, and soil fertility (Duguma and Tonye 1994). Binkley et al. (1992) demonstrated the advantages of *F. falcata* tree additions to *Eucalyptus saligna* tree plantation growth in Hawai'i; they found that mixed stands of *E.*

FIGURE 6. Downed *F. falcata* trees in the Puna district of Hawai'i Island following Tropical Storm Iselle in 2014 (www.KHON.com).

saligna and *F. falcata* exhibited higher levels of biomass, greater net primary production, and increased annual increment values relative to monocultures of either species. Such mixed-stand increases were largely attributed to concomitant increases in soil N availability stemming from elevated N-fixation by *F. falcata* (Garcia-Montiel and Binkley 1998), though declines in soil P availability with *F. falcata* presence were also noted (Binkley et al. 2000). *F. falcata* has also been a component of productive agroforestry systems in countries where labor is abundant and economic resources are limited; the wood is used for firewood, as energy for industry, and timber for construction. The nutrient-rich biomass of the tree is used to increase soil N availability and increase crop yields (Zabala 1997). In Western Java, *F. falcata* is used for furniture, light construction, paper pulp, and rayon cloth (Krisnawati et al. 2011). The tree is commonly used to make fiberboard, boxes, chopsticks, musical instruments, plywood veneers, and timber for light construction in many regions of Southeast Asia (Garcia 1989).

F. falcata is also used in small mixed-crop farms throughout humid tropics of the Pacific Basin to promote soil fertility and provide shade for crops, fodder for livestock, and lumber for humans. It is grown as a resource in home gardens of Western Samoa and the Philippines (Garcia 1989), and it is similarly utilized throughout its native range of the Solomon Islands, Papua New Guinea, and other islands of Indonesia. In Kediri, East Java, *F. falcata* plantations mixed with pineapple are established because they are profitable and provide reliable income to communities (Siregar et al. 2007). Nandini et al. (2023) found that cropping of small taro (*Colocasia esculenta*), ginger (*Zingiber officinale*), and vanilla (*Vanilla planifolia*) under *F. falcata* stands increased productivity of private forests and farmers' income in West Nusa Tenggara, Indonesia. Farmers in the Philippines contracted to grow trees for commercial harvest also intercropped corn, cassava, and bananas among rows of young *F. falcata* trees (Estoquia 1997), and coffee plantations in Indonesia also were intercropped with *F. falcata* to increase shade and soil fertility (Djogo 1997). Incorporation of *F. falcata* into farming practices of the Baduy people of West Java highlights its positive effect on soil fertility. Traditional swidden farming is central to Baduy culture, and use of chemical fertilizers or other modern inputs is frowned upon. However, intercropping of *F. falcata* was welcomed when farmers recognized the improved soil fertility imparted by the trees to their swiddens (Iskandar and Ellen 2000). In Hawaii, *F. falcata* wood has proved a suitable growth medium for oyster mushroom (*Pleurotus ostreatus*) in greenhouse settings (Tisdale et al. 2006).

The ability of *F. falcata* to provide nitrogen, weed control, organic matter, and shade has been demonstrated in agroforestry field trials, though some studies have concluded that the tree grows *too* well. As such, the species often has been characterized as an invasive weed tree rather than the "multipurpose tree species" it was seen as up to the 1990s (Zabala 1997). A trial of fast-growing tree species on Hawai'i Island was interrupted because *F. falcata* was growing too rapidly and shading out the other trial species; two-year-old trees that were 9–12 m tall had to be cut down to release other tree species' growth; as a result, the tree was recommended for planting across the region to meet local demand for wood (Walters 1971). Evensen (1989) found *F. falcata* best performing among three N-fixing tree species in cropping trials in Sumatra; the tree increased adjacent rice and cowpea yields by 2 times and 4 times, respectively. Similarly, *Eucalyptus* seedlings and trees planted in combination with *F. falcata* in plantation settings on Hawai'i Island grew faster than eucalyptus grown by itself (DeBell et al. 1987, Binkley 1997). Despite these agroforestry benefits, the easy availability of synthetic fertilizers and the high cost of labor makes alley cropping or green manure solutions involving *F. falcata* less profitable in the United States.

Although *F. falcata* wood is used for light construction and industry in the Philippines and Indonesia, U.S. construction standards have prohibited use of such light wood as building lumber. However, recent research found *F. falcata* wood as strong as Douglas fir

in comparable stress tests (Allen 2018), and *F. falcata* wood has been used to build an example of a small home whose production could be scaled-up to meet future multi-unit temporary and/or emergency housing needs (thealbiziaproject.com) (Figure 7). Further, results from Corpataux et al. (2020) suggest that *F. falcata* has potential to be successfully used for cross-laminated timber in Southeast Asia's construction industry. *F. falcata* also has been used to make surfboards, flooring, and small furniture in Hawai'i, but currently no forest product industry exists to expand upon such efforts.

Because they are fast-growing, *F. falcata* stands have the potential to store significant amounts of carbon in live biomass over relatively short periods of time (Mascaro et al. 2012). Landscape-scale analysis of dynamics of primary succession in wet lowland forests of Hawai'i indicated that *F. falcata*-dominated stands accumulated up to 130 Mg of aboveground carbon per hectare in less than 80 years, whereas native-dominated forest stands of the same region required approximately 300 years of successional development to attain comparable levels of aboveground carbon (Hughes et al. 2014). Further, *F. falcata* stands undergoing secondary succession following deforestation in lowland wet regions of Hawai'i Island exhibited aboveground C mass values averaging 123 Mg C ha^{-1} after less than 3 decades of growth, with annual accumulation rates averaging 4.6 Mg C ha^{-1} y^{-1}. Such aboveground C mass pools were comparable to those of mature tropical wet forests found elsewhere (Hughes et al. 2022), and demonstrated accumulation rates were on par with fast-growing second-growth forests of the Continental Tropics that have been noted for their appealingly high C mass sequestration potential (Poorter et al. 2016).

FIGURE 7. Image and front view, of small home, "LIKA," model constructed with *Falcataria falcata* lumber on University of Hawai'i at Mānoa campus. Photo credit: The Albizia Project.

Although aboveground C accumulation in live biomass of *F. falcata* stands is typically rapid during both primary and secondary succession, residence times of stored C may not be long in duration compared to other forest systems. Hughes and Uowolo (2006) found that leaf litter decomposed up to an order of magnitude faster in *F. falcata* stands relative to comparable native-dominated forest counterparts in wet lowland environments of Hawai'i. Allison et al. (2006) determined that *F. falcata* invasion altered the composition and function of belowground soil communities to promote rapid microbial processing of organic matter. In addition, *F. falcata* trunks and limbs exhibit relatively low wood density values (i.e., 0.30 g cm^3) making them prone to rapid decomposition (RF Hughes unpublished data). Collectively, these factors impel fine and coarse litter inputs to be rapidly decomposed within *F. falcata* stands, potentially reducing prospects for long-term ecosystem C storage relative to native *M. polymorpha*-dominated forests and other forest types in Hawai'i (DiManno et al. 2023) and other Pacific Islands.

F. falcata may be considered useful as an organic soil amendment and tool for climate-smart agricultural practices. Norton (2019) examined whether compost from *F. falcata* trees could replace or partially replace chemical fertilizer and store carbon in agricultural lands on the windward side of Hawai'i Island. The potential benefits from

this approach included control of invasive species, carbon sequestration, avoidance of inorganic fertilizer use, and reduction of reactive nitrogen emissions (Lal 2010). Trials included two crops, *Zea mays* (corn) and *Manihot esculenta* (cassava) planted across a spectrum of East Hawai'i farmland sites, which varied in land use history and associated degrees of soil degradation. Treatments included standard applications of chemical fertilizer, application of *F. falcata* compost, and combinations of chemical fertilizer and compost (Norton 2019). Harvest yields of corn crops showed that *F. falcata* compost did not provide a level of fertility equal to that provided by chemical fertilizer, likely because corn is a short-term crop that requires abundant soil nitrogen in highly available forms. In contrast, cassava, a root crop, exhibited yields when fertilized with *F. falcata* compost that were equal to yields from fields receiving chemical fertilizer amendments (Figure 8). Overall, crop yield response to *F. falcata* compost application was highly variable among site locations, with yield responses tending to be higher for degraded farm sites amended with *F. falcata* compost compared to more fertile farm sites amended with *F. falcata* compost (Norton 2019). This high variability in yield response to fertility treatments among sites was also exhibited by control treatments and resulted in no difference among treatments (Norton 2019).

In addition to potential benefits derived from *F. falcata* "green manure" use, avoided economic and carbon costs associated with

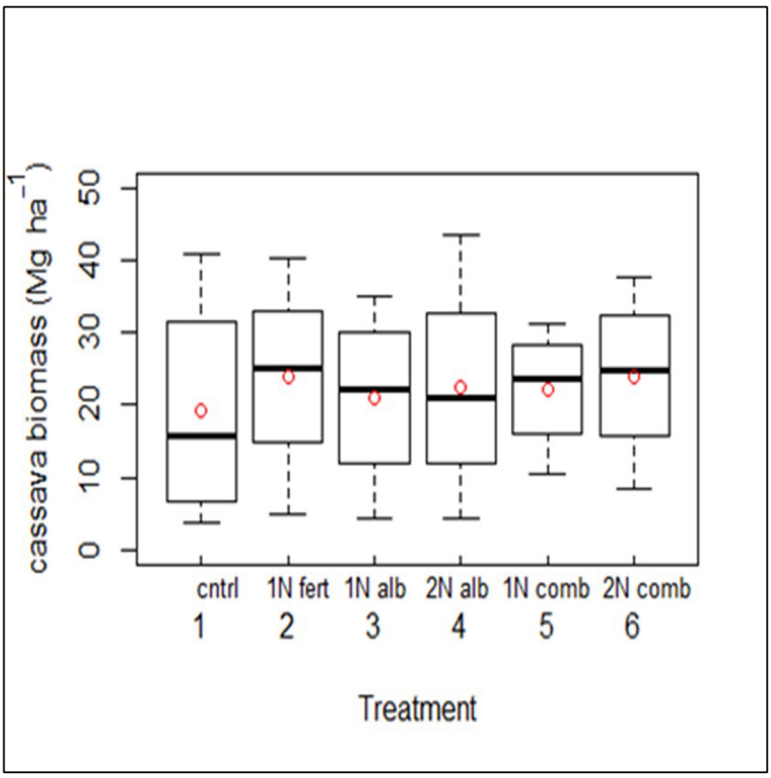

FIGURE 8. Mean values (red circle), median values (bold, black horizontal line), upper and lower quartile values (bottom and top edge of box), and minimum/maximum values (error bar) of Cassava (*Manihot esculenta*) biomass in fertilization experiments comparing yield responses to chemical inorganic fertilizer and *F. falcata* organic compost amendments. Treatment 1 = control plots; Treatment 2 (1N fertilizer) = typical inorganic N fertilizer application (80 kg N/ha); Treatment 3 (1N albizia compost) and Treatment 4 (2N albizia compost) defined two levels of organic *F. falcata* compost application. Treatments 5 and 6 = combinations of *F. falcata* and inorganic N fertilizer (Norton 2019).

TABLE 3

A Partial Analysis of Economic and Carbon Costs, Carbon Storage for Each Treatment in the Cassava Trials

Treatment	Economic Cost ($ kg yield^{-1})	CO_2 Emissions (kg CO_2 kg yield^{-1})	Increase in Soil C (Mg C ha^{-1})	CO_2 Emissions (Mg CO_2 ha^{-1})	Total C Gain or Loss (Mg ha^{-1})
(1) control	0.00 (0.00)[a]	0.00 (0.00)[a]	0.00 (0.00)	0.00	0.00 (0.00)
(2) 1N fert	0.041 (0.037)[ab]	0.061 (0.055)[ab]	7.38 (9.27)	0.36	7.28 (9.27)
(3) 1N *F. falcata*	0.024 (0.022)[ab]	0.064 (0.059)[ab]	7.94 (10.2)	0.32	7.86 (10.2)
(4) 2N *F. falcata*	0.048 (0.046)[ab]	0.126 (0.119)[ab]	7.11 (9.33)	0.64	6.94 (9.33)
(5) 1N combo	0.033 (0.012)[ab]	0.067 (0.024)[ab]	6.96 (10.2)	0.50	6.83 (10.2)
(6) 2N combo	0.072 (0.040)[b]	0.148 (0.083)[b]	8.02 (11.3)	1.00	7.75 (11.3)
F stat					
χ^2	13.91	13.93			10.003
df	5	5			5
P-value	0.016	0.016			0.075
Transformed	No	No			No

Note: Economic costs included urea fertilizer and fuel cost for chipper use. Carbon costs included carbon emitted from fertilizer production and transport and carbon emitted from chipper (Norton 2019).

chemical fertilizer use are important to consider. Norton (2019) found that costs were generally not different between *F. falcata* and chemical fertilizer (Table 3). The amount of carbon gained or lost was also similar across treatments (Table 3), indicating that climate-smart agriculture using *F. falcata* compost may be a viable alternative to chemical fertilizer. Results pointed to the potential for *F. falcata* to decrease chemical fertilizer use and store carbon in farmland soils as part of climate-smart agricultural techniques.

Regulatory Aspects

At present, *F. falcata* is not a member of the Hawai'i Department of Agriculture's Noxious Weed List, and no regulations prohibit importation or commercial use of the tree. However, the species has been determined by the Hawai'i Pacific Weed Risk Assessment as a high-risk species and one to avoid planting (Daehler et al. 2004, https://plantpono.org/high-risk-plants/).

RESPONSE TO MANAGEMENT

Given *F. falcata*'s salient characteristics—rapid growth, large stature, symbiotic N-fixation capacity, copious seed production, and subsequent seed bank—prospects for its management would seem daunting and expensive. Yet management approaches to control *F. falcata* can be effective, particularly those that work in concert to exploit the trees' intrinsic weaknesses and that align with natural tendencies of ecosystems to deter subsequent reestablishment of *F. falcata*.

Such an approach was employed on Tutuila Island, American Samoa, where *F. falcata* had invaded forests and displaced native Samoan trees to the point that over 60% of the biomass of invaded forest plots was accounted for by *F. falcata* (Hughes et al. 2013). Management actions within and around the National Park of American Samoa (NPAS) to remove *F. falcata* trees were executed by field crews who incised the bark of trees at their base and manually peeled the bark off in large strips around the entirety of the trunk, resulting in a 1–3 m wide girdled section of the tree. Individual trees died gradually and inevitably 6–12 months following treatment (Hughes et al. 2013). NPAS field crews killed thousands of mature trees in efforts to restore approximately 1,500 ha of native Samoan forest. Following removal of *F. falcata* (i.e., killing of mature individuals), native Samoan tree species grew rapidly to fill resulting forest gaps and created a closed canopy forest that

preempted reinvasion by *F. falcata*. Presence of fast-growing early successional native Samoan tree species appeared to be the most important reason why *F. falcata* was inhibited from reestablishing. Once *F. falcata* was removed, native tree species promptly exploited the legacy of increased available soil N—left from years of *F. falcata* litter inputs—to successfully capture resulting light gaps and effectively eliminate recruitment by shade-intolerant *F. falcata* seedlings (Hughes et al. 2012). In this manner, not only were large, dominant canopies of *F. falcata* eliminated from native Samoan forests by these management actions and the native forest successional response to them, but the prodigious *F. falcata* seed bank was effectively suppressed, thus breaking the cycle of reinvasion. In cases where native island floras such as that of Hawai'i lack many fast-growing early successional species, vegetation capture of nutrient-rich light gap environments in the wake of *F. falcata* management may take the form of non-native—but importantly non-*F. falcata*—species whose growth and forest floor light suppression is nonetheless critical to prohibiting germination of extant *F. falcata* seed banks.

Chemical Control

Chemical herbicides most effective in *F. falcata* control include Garlon 3A and Milestone® containing active ingredients triclopyr and aminopyralid, respectively (Hughes et al. 2013). Garlon 3A is applied to girdled portions of trees, while Milestone® is applied via low-volume, high-concentration injections; both produce mortality rates near 100% (Hughes et al. 2013). The application efficiency of Milestone® make it preferable for *F. falcata* management throughout the Pacific Islands (Hughes et al. 2013). The method is safer and more effective than current conventional methods and allows for efficient control of *F. falcata* populations across Hawai'i where large numbers of non-hazardous trees (i.e., those that can be killed and left standing without risk of property damage or bodily harm) can be dispatched relatively cheaply and easily. On Hawai'i Island, the Big Island Invasive Species Committee (BIISC, www.biisc.org) has been instrumental in working with State and County agencies, utility companies, and community organizations to control unwanted *F. falcata* stands. Typically, partners working with BIISC cut down and remove the subset of trees deemed hazardous (i.e., individuals growing adjacent to infrastructure) in *F. falcata* stands, and BIISC staff chemically treat the more numerous non-hazardous trees that can be safely killed and allowed to decompose in place over the course of several years without danger to people or infrastructure. This approach has proven highly successful and cost effective in reducing the number and extent of *F. falcata* populations across Hawai'i Island (Niemiec et al. 2020).

Socio-Economic Aspects of F. falcata *Management*

Whether or not management actions to control *F. falcata* stands in natural areas or human-built areas are implemented often depends as much on socio-economic factors and forces as ecological considerations. In American Samoa, agency support provided significant funding to implement *F. falcata* control measures across targeted areas, and overwhelming public support for *F. falcata* control efforts was cultivated through public outreach and informational meetings with local village leadership, gainful employment of villagers from areas adjacent to infestations, and use of media outlets on a consistent basis. In addition, because *F. falcata* individuals were easily viewed within upslope forests, their demise following control treatments was readily apparent to village residents, a fact which underscored the success of the program in protecting American Samoa's native forests from invasion (Hughes et al. 2013). Further, on the Hawaiian Island of Moloka'i the impetus to control *F. falcata* in forests where it had invaded derived from public concern that the extensive root systems of mature stands were destroying important cultural sites. These concerns prompted a concerted response from the Moloka'i Invasive Species Committee that resulted in successful island-wide eradication of *F. falcata*.

Large-scale efforts to control *F. falcata* occurred on Hawai'i Island in the aftermath of Tropical Storm Iselle, which hit that island in the summer of 2014. The extensive and costly damage of Tropical Storm Iselle, much of it due to catastrophic failure of large *F. falcata* trees, created acute public concern for the health and welfare of communities living around these large trees which, in turn, catalyzed multi-agency and private landowner efforts to prioritize *F. falcata* control within residential areas and along transportation and energy corridors (Niemiec et al. 2020). During the ensuing 3 years after the storm, BIISC and Hawai'i Island partners eliminated approximately 250,000 *F. falcata* individuals that collectively had posed an imminent threat to residential areas, power lines, and transportation corridors (www.biisc.org); such management efforts continue to be successfully employed where needed.

Biological Control

Biological control methods for *F. falcata* management are not yet available. However, a variety of organisms have been identified as potential biological control agents. Among these is a gall rust fungus (*Uromycladium falcatarium*) which infects *F. falcata* in Malaysian plantations (Rahayu et al. 2009, Rahayu et al. 2010). Ji et al. (2017) identified a significant canker disease of *F. falcata* caused by *Lasiodiplodia theobromae* in subtropical Southern China. Bitume (2021) identified eriophyid mites (Vidović et al. 2023) and a stem boring weevil from Indonesia as candidate biocontrol agents. Host species specificity is a necessary condition for successful biological control, as introduction of biological control agents which could harm native species or commercially important crops is strictly prohibited. Further research will determine host specificity of the candidate agents throughout *F. falcata*'s introduced range (Bitume 2021).

PROGNOSIS

F. falcata is an ecosystem engineer (Jones et al. 1994) in the sense that its invasive properties influence physical resources (Crooks 2002). The tree increases soil nutrient availability to other species through its nitrogen-fixation capacity and high litterfall rates, and disturbance regimes are affected by its rapid growth and sprawling canopy. It transforms the composition, structure, and function of wet forest, riparian, and aquatic habitats, significantly decreasing native biodiversity where it invades. Additionally, *F. falcata* is recognized as impacting people directly by damaging residential and business infrastructure as well as transportation corridors. While not yet studied, climate warming may increase the elevational range of this species, and predicted storms of increasing frequency and intensity may lead to more catastrophic *F. falcata* tree fall events.

Given the well-documented threats of this species to native ecosystems and human infrastructure, increased management efforts and development of alternative uses for the tree are warranted. Effective chemical techniques to control *F. falcata* in targeted localized sites have been developed and implemented to good effect. Because such approaches may not be feasible or appropriate for certain communities and settings, development of an effective biological control agent for large-scale *F. falcata* throughout the Pacific Islands would be of great utility. In addition, agroforestry use of the tree for mulch, weed control, and shade has been employed in small-scale agriculture in its native range, and there is potential to substitute *F. falcata* mulch for chemical fertilizers in its introduced range as well, particularly where fertilizer prices are high. *F. falcata* has also shown potential as a biofuel in Java, Indonesia (Siregar et al. 2017), and research to determine if such use is appropriate and economically viable for Pacific Island nations would be useful. Further efforts regarding *F. falcata* would do well to focus on its management, potential uses, the restoration of invaded areas, as well as social and economic factors that might galvanize communities to reduce the spread and impact of the tree to maintain healthy native ecosystems within the Pacific Islands.

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Literature Cited

Albizia Project Committee. 2015. Albizia emergency tree mitigation and management plan. Prepared for HELCO, Hilo, Hawai'i.

Allen, T. C. 2018. Material testing of *Albizia* lumber for structural applications. Plan B Master's Non-Thesis, Department of Natural Resources and Environmental Management, College of Tropical Agriculture and Human Resources, University of Hawai'i at Mānoa, Honolulu.

Allison, S. D., C. Nielsen, and R. F. Hughes. 2006. Elevated enzyme activities in soils under the invasive nitrogen-fixing tree *Falcataria moluccana*. Soil Biol. Biochem. 38:1537–1544.

Asner, G. P., R. F. Hughes, P. M. Vitousek, D. E. Knapp, T. Kennedy-Bowdoin, J. Boardman, R. E. Martin, M. Eastwood, and R. O. Green. 2008. Invasive plants transform the three-dimensional structure of rain forests. Proc. Natl. Acad. Sci. U.S.A. 105:4519–4523.

Atkinson, I. A. E. 1970. Successional trends in the coastal and lowland forest of Mauna Loa and Kilauea volcanoes, Hawai'i. Pac. Sci. 24:387–400.

Baskorowati, L., D. Bush, D. Setiadi, and M. Susanto, M. 2017. Genetic variation of growth and disease resistance traits in open-pollinated provenance-progeny trials of *Falcataria moluccana* growing on two rust-affected sites at age-18 months. J. Man. Hut. Trop. 23:1–7.

BIISC. 2019. BIISC: Albizia. Available from http://www.biisc.org/albizia/.

Binkley, D. 1997. Bioassays of the influence of *Eucalyptus saligna* and *Albizia falcataria* on soil nutrient supply and limitation. For. Ecol. Manag. 91:229–234.

Binkley, D., K. A. Dunkin, D. Debell, and M. G. Ryan. 1992. Production and nutrient cycling in mixed plantations of *Eucalyptus* and *Albizia* in Hawaii. For. Sci. 38(2):393–408.

Binkley, D., C. Giardina, and M. A. Bashkin. 2000. Soil phosphorus pools and supply under the influence of *Eucalyptus saligna* and nitrogen-fixing *Albizia falcataria*. For. Ecol. Manag. 128(3):241–247.

Binkley, D., R. Senock, and K. Cromack, Jr. 2003. Phosphorus limitation on nitrogen fixation by *Falcataria* seedlings. For. Ecol. Manag. 186:171–176.

Bitume, E. 2021. The biological control process and describe the next steps in our international collaboration with researchers in Indonesia to find appropriate natural enemies of Albizia. IOP Conf. Ser.: Earth Environ. Sci. 694(1):012002. https://doi.org/10.1088/1755-1315/694/1/012002.

Boydon, S., D. Binkley, and R. Senock. 2005. Competition and facilitation between *Eucalyptus* and nitrogen-fixing *Falcataria* in relation to soil fertility. Ecology 86:992–1001.

Butler, R. A. 2014. Invasive species worsen damage from Hawaii's storms. Mongabay. URL http://news.mongabay.com/2014/08/invasive-species-worsen-damage-from-Hawaiis-storms/.

Christophersen, E. 1938. Flowering plants of Samoa. II. Bernice P. Bishop Museum Bulletin 154:1–77.

Corpataux, L., S. Okuda, and H. W. Kua. 2020. Panel and plate properties of cross-laminated timber (CLT) with tropical fast-growing timber species in compliance with Eurocode 5. Constr. Build. Mater. 261:119672. https://doi.org/10.1016/j.conbuildmat.2020.119672.

Crooks, J. A. 2002. Characterizing ecosystem-level consequences of biological invasions: the role of ecosystem engineers. Oikos 97:153–166.

Daehler, C. C., J. S. Denslow, S. Ansar, and H. Kuo. 2004. A risk assessment system for screening out invasive pest plants from

Hawai'i and other Pacific Islands. Conserv. Biol. 18:360–368.
DeBell, D. S., C. D. Whitesell, and T. B. Crabb. 1987. Benefits of *Eucalyptus-Albizia* mixtures vary by site on Hawaii Island. Res. Paper PSW-187. U.S. Forest Service, USDA.
DiManno, N., R. Ostertag, A. Uowolo, A. Durham, K. Blakemore, S. Cordell, and P. Vitousek. 2023. Functional trait-based restoration alters nutrient cycling and invasion rates in Hawaiian lowland wet forest. Ecol. Appl. 33(6):e2894. https://doi.org/10.1002/eap.2894.
Djogo, A. P. Y. 1997. Use of *Albizia* species in small-scale farming systems in Indonesia. Pages 27–36 *in* N. Q. Zabala, ed. International workshop on *Albizia* and *Paraserianthes* species. Proceedings of a workshop held on November 13–19, 1994, in Bislig, Surigao del Sur, Philippines. Forest, Farm, and Community Tree Research Reports (special issue). Winrock International, Morrilton, Arkansas, USA.
Duguma, B., and J. Tonye. 1994. Screening of multipurpose and shrub species for agroforestry in the humid lowlands of Cameroon. For. Ecol. Manag. 64:135–143.
Estoquia, D. A. 1997. The farming of *Paraserianthes falcataria*: successes and problems of a tree farmer in Surigao del Sur. Pages 128–130 *in* N. Q. Zabala, ed. International workshop on *Albizia* and *Paraserianthes* species. Proceedings of a workshop held on November 13–19, 1994, in Bislig, Surigao del Sur, Philippines. Forest, Farm, and Community Tree Research Reports (special issue). Winrock International, Morrilton, Arkansas, USA.
Evensen, C. L. I. 1989. Alley cropping and green manuring for upland crop production in West Sumatra. Ph.D. diss., University of Hawai'i at Mānoa, Honolulu.
Footman, T. 2001. Guinness World Records 2001. Little Brown & Co., New York. 288 pp.
Garcia, M. U. 1989. NFT highlights. *Paraserianthes falcataria*: Southeast Asia's growth champion. Nitrogen-Fixing Tree Association: 89-05.
Garcia-Montiel, D. C., and D. Binkley. 1998. Effect of *Eucalyptus saligna* and *Albizia falcataria* on soil processes and nitrogen supply in Hawaii. Oecologia 113:547–556.
GBIF.org. 2023. Global Biodiversity Information Facility-Occurrence Download. https://doi.org/10.15468/dl.psze27.
Hall, S. J., D. P. Huber, and R. F. Hughes. 2018. Invasion of Hawaiian rainforests by an introduced amphibian predator and N_2-fixing tree increases soil N_2O emissions. Ecosphere 9:e02416.
Houlton, B. Z., Y. P. Wang, P. M. Vitousek, and C. B. Field. 2008. A unifying framework for dinitrogen fixation in the terrestrial biosphere. Nature 454:327–330.
Hughes, F., T. Johnson, and A. Uowolo. 2013. The invasive alien tree *Falcataria moluccana*: its impacts and management. Session 5 Prospects for Weed Biological Control in Pacific Islands; XIII International Symposium on Biological Control of Weeds.
Hughes, R. F., and J. S. Denslow. 2005. Invasion by a N_2-fixing tree alters function and structure in wet lowland forests of Hawaii. Ecol. Appl. 15:1615–1628.
Hughes, R. F., and A. Uowolo. 2006. Impacts of *Falcataria moluccana* invasion on decomposition in Hawaiian lowland wet forests: the importance of stand-level controls. Ecosystems 9:977–991.
Hughes, R. F., A. L. Uowolo, and T. P. Togia. 2012. Recovery of native forest after removal of an invasive tree, *Falcataria moluccana*, in American Samoa. Biol. Invasions 14:1393–1413.
Hughes, R. F., G. P. Asner, J. Mascaro, A. Uowolo, and J. Baldwin. 2014. Carbon storage landscapes of lowland Hawaii: the role of native and invasive species through space and time. Ecol. Appl. 24(4):716–731.
Hughes, R. F., D. Grossman, T. G. Sowards, J. D. Marshall, and D. Mueller-Dombois. 2022. Aboveground carbon accumulation by second-growth forests after deforestation in Hawai'i. Ecol. Appl. 32:e2539.
Iskandar, J., and R. F. Ellen. 2000. The contribution of *Paraserianthes* (*Albizia*) *falcataria* to sustainable swidden manage-

ment practices among The Baduy of West Java. Hum. Ecol. 28:1–17.
Ji, C. Y., C. J. Chen, X. R. Wang, Y. Liu, J. Y. Liu, and B. S. Zeng. 2017. A report on canker disease of *Falcataria moluccana* caused by *Lasiodiplodia theobromae* in China. Crop Protect. 91:89–92.
Jones, C. G., J. H. Lawton, and M. Shachak. 1994. Organisms as ecosystem engineers. Oikos 69:373–386.
Kawai, K., T. Kenzo, S. Ito, and K. Kanna. 2023. Size-related changes in leaf, wood, and bark traits in even-aged *Falcataria falcata* trees. Tropics 32:15–27.
Krisnawati, H., E. Varis, M. Kallio, and M. Kanninen. 2011. *Paraserianthes falcataria* (L.) Nielsen: Ecology, silviculture, and productivity. CIFOR, Bogor, Indonesia.
Kueffer, C. 2010. Reduced risk for positive soil-feedback on seedling regeneration by invasive trees on a very nutrient-poor soil in Seychelles. Biol. Invasions 12:97–102.
Lal, R. 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. BioScience 60:708–721.
Larcher, W. 1980. Physiological plant ecology. Springer-Verlag, New York, NY, USA.
Little, E. L., Jr., and R. G. Skolmen. 1989. Common forest trees of Hawaii. USDA Agriculture Handbook No 679. United States Department of Agriculture, Washington, DC, USA. 321 pp.
Marschner, H. 1995. Mineral nutrition of higher plants. Academic Press, Harcourt-Brace and Company, Publishers, New York, NY, USA. 889 pp.
Mascaro, J. T., R. F. Hughes, and S. A. Schnitzer. 2012. Novel forests maintain ecosystem processes after decline of native tree species. Ecol. Monogr. 82:221–38.
Meyer, J. 2007. Conserving natural forests and managing protected areas in French Polynesia. Bois et Forêts des Tropiques 291:25–40.
Motooka, P., L. Castro, D. Nelson, G. Nagai, and L. Ching. 2011. Weeds of Hawaii's pastures and natural areas: An identification and management guide. University of Hawai'i at Mānoa, Honolulu.
Mueller-Dombois, D., and F. R. Fosberg. 1998. Vegetation of the tropical Pacific Islands. Springer-Verlag, New York.
Nandini, R., I. W. W. Susila, R. Agustarini, and G. Samawandana. 2023. Evaluating agroforestry patterns to increase land productivity of *Falcataria moluccana* private forests in Central Lombok Regency, West Nusa Tenggara. For. Soc. 7:247–262.
Niemiec, R. M., G. P. Asner, P. G. Brodrick, J. A. Gaertner, and N. M. Ardoin. 2018. Scale-dependence of environmental and socioeconomic drivers of albizia invasion in Hawaii. Landsc. Urban Plan. 169:70–80.
Niemiec, R. M., G. P. Asner, P. G. Brodrick, N. Vaughn, J. Heckler, R. F. Hughes, L. Keith, and T. Matsumoto. 2020. Using spatially explicit, time-dependent analysis to understand how social factors influence conservation outcomes. Conserv. Biol. 34: 505–514.
Nissen, T. M., and D. J. Midmore. 2002. Stand basal area as an index of tree competition in timber intercropping. Agrofor. Syst. 54:51–60.
Norton, J. 2019. Can compost from a nitrogen-fixing tree, *Falcataria moluccana*, replace chemical fertilizer and store carbon in agricultural systems? M.S. thesis, University of Hawai'i at Hilo, Hilo.
Otsamo, R. 2000. Secondary forest regeneration under fast growing forest plantations on degraded *Imperata cylindrica* grasslands. New Forests 19:69–93.
Owen, S. M., O. Kuegler, A. D. Lehman, R. F. Hughes, J. Terzibashian, I. Sprecher, T. Thompson, S. Ayotte, M. Yatskov, and M. Silva. 2021. Hawai'i's forest resources: Forest inventory and analysis, 2010–2015. General Technical Report PNW-GTR. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
Parrotta, J. A. 1990. *Paraserianthes falcataria* (L.) Nielsen, Batai, Moluccan Sau: Leguminosae (Mimosoideae), legume family. US Forest Service, Southern Forest Experiment Station, Institute of Tropical Forestry.

Pasiecznik, N. 2014. Invasive Species Compendium: *Albizia chinensis* (Chinese albizia). CABI Compendium (cabidigitallibrary.org).

PIER. 2014. Pacific Islands Ecosystems at Risk. HEAR, University of Hawai'i, Honolulu. http://www.hear.org/pier/index.html.

Poorter, L., F. Bongers, T. M. Aide, A. M. Almeyda Zambrano, P. Balvanera, J. M. Becknell, V. Boukili, et al. 2016. Biomass resilience of neotropical secondary forests. Nature 530:211–4.

POWO. 2023. Plants of the World Online. Facilitated by the Royal Botanic Gardens, Kew. Published on the Internet; http://www.plantsoftheworldonline.org [Retrieved 12 September 2023].

Rahayu, S., N. A. A. Shukor, L. S. See, and G. Saleh. 2009. Responses of *Falcataria moluccana* seedlings of different seed sources to inoculation with *Uromycladium tepperianum*. Silvae Genetica 58:62–68.

Rahayu, S., S. S. Lee, and N. A. A. Shukor. 2010. *Uromycladium tepperianum*, the gall rust fungus from *Falcataria moluccana* in Malaysia and Indonesia. Mycoscience 51: 149–153.

Rock, J. F. 1920. The leguminous plants of Hawaii. Experiment Station of the Hawaiian Sugar Planters Association, Honolulu, Hawaii.

Rojas-Sandoval, J. 2023. Invasive Species Compendium: *Falcataria moluccana* (batai wood). CABI Compendium (cabidigitallibrary.org).

Siregar, U. J., A. Rachmi, M. Y. Massijaya, N. Ishibashi, and K. Ando. 2007. Economic analysis of sengon (*Paraserianthes falcataria*) community forest plantation, a fast-growing species in East Java, Indonesia. For. Policy Econ. 9:822–829.

Siregar, U. J., B. H. Narendra, J. Suryana, C. A. Siregar, and C. Weston. 2017. Evaluation on community tree plantations as sustainable source for rural bioenergy in Indonesia. IOP Conf. Ser.: Earth Environ. Sci. 65:012019.

Soerianegara, I., and R. H. M. J. Lemmens. 1993. Plant resources of South-east Asia. No. 5 (1): Timber trees: major commercial timbers. Pudoc Scientific Publishers, Wageningen.

Starr, F., K. Starr, and L. Loope. 2003. *Falcataria moluccana*: Molucca albizia: Fabaceae. United States Geological Survey: Biological Resources Division. Accessed 21 April 2022. http://www.hear.org/starr/hiplants/reports/pdf/falcataria_moluccana.pdf.

Tisdale, T. E., S. C. Miyasaka, and D. E. Hemmes. 2006. Cultivation of the oyster mushroom (*Pleurotus ostreatus*) on wood substrates in Hawaii. World J. Microbiol. Biotechnol. 22:201–206.

Tuttle, N. C., K. H. Beard, and W. C. Pitt. 2009. Invasive litter, not an invasive insectivore, determines invertebrate communities in Hawaiian forests. Biol. Invasions 11:845–855.

Vidović, B., T. Cvrković, and O. Warea Orapa. 2023. A new genus and new species of eriophyid mites from Papua New Guinea: a potential biological control agent of *Falcataria moluccana* (Fabaceae). Acarologia 63(3):933–944. https://doi.org/10.24349/w78m-2mk8.

Vitousek, P. M., and H. Farrington. 1997. Nutrient limitation and soil development: experimental test of a biogeochemical theory. Biogeochemistry 37:63–75.

Vitousek, P. M., and L. R. Walker. 1989. Biological invasion by *Myrica faya* in Hawaii: plant demography, nitrogen fixation, ecosystem effects. Ecol. Monogr. 59: 247–265.

Vitousek, P. M., L. L. Loope, and C. P. Stone. 1987. Introduced species in Hawai'i: biological effects and opportunities for ecological research. Trends Ecol. Evol. 2:224–227.

Wagner, W., D. Herbst, and S. Sohmen. 1999. Manual of the flowering plants of Hawai'i. Volume 1. Bishop Museum Special Publication 83. University of Hawai'i and Bishop Museum Press, Honolulu.

Wagner, W. L., and N. R. Khan. 2023. Flora of the Hawaiian Islands website. Accessed June 2023. https://naturalhistory2.si.edu/botany/hawaiianflora/.

Walters, G. A. 1971. A species that grew too fast – *Albizia falcataria*. J. For. 69:168.

Watson, J. C. 2018. Strategic plan for the control and management of Albizia in Hawai'i. Hawai'i Invasive Species Council.

Wiegner, T. N., R. F. Hughes, L. M. Shizuma, D. K. Bishaw, and M. E. Manuel. 2013. Impacts of an invasive N_2-fixing tree on Hawaiian stream water quality. Biotropica 45:409–418.

Woodcock, D. 2003. To restore the watersheds: early 20th century tree planting in Hawaii. Ann. Assoc. Am. Geogr. 93:624–635.

Zabala, N. Q., ed. 1997. International workshop on *Albizia* and *Paraserianthes* species. Proceedings of a workshop held November 13–19, 1994, in Bislig, Surigao del Sur, Philippines. Forest, Farm, and Community Tree Research Reports (special issue). Winrock International, Morrilton, Arkansas, USA.