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# Satellite imagery reveals widespread coconut plantations on Pacific atolls

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## Abstract

Efforts to mitigate tropical deforestation overlook coconut palm (*Cocos nucifera* L.) plantations on atolls—low island ecosystems that represent the most common landforms in the Pacific basin. Coconut palms have a deep history in the Pacific and were planted extensively over the last two centuries to meet the surging demand for coconut oil exports. But despite wide interest in the global footprint of palm crops, the distribution of coconut palms on Pacific atolls has remained unknown. We applied a supervised machine learning classifier to satellite imagery to produce 2 m resolution vegetation maps of 235 of 266 Pacific atolls. Despite the abandonment of many plantations in recent decades, we find that coconut palms surpass native broadleaf trees in terms of canopy area: coconut presently covers 58.3% of the mapped atolls' total forested area and 24.1% of their total land area. 51.2% of these coconut canopies occur in monocultures indicative of plantation agriculture and drastic ecological changes. Even among atolls with climates equally suitable for coconut palms, coconut canopy coverage is 32.1 percentage points greater on those that historically exported coconut products, demonstrating the significant and persistent effects of plantations on forest compositions in the tropical Pacific. Coconut palms are most dominant on large, wet islands, reflecting their high rates of water use and thus their potential to deplete critical groundwater resources. The spread of coconut plantations also came at the expense of native vegetation critical for wildlife habitat, nutrient cycling, and soil formation. The severe environmental impacts of coconut plantations urge ecosystem management in a region uniquely exposed to climate change.

## 1. Introduction

Atolls are unique ecosystems of the tropical Indo-Pacific. Their reef islands comprise over a third of all Pacific islands, making them the most common and widely distributed landform within the Pacific basin [1]. The 266 atolls of the Pacific form vast ecological networks that provide key breeding grounds for many seabirds and marine species [2–5], drive marine productivity and dispersal in some of the Earth's most oligotrophic waters [6–9], and support over 220 000 human inhabitants [10].

Despite the popular perception of atolls as unspoiled paradise, many bear deep legacies of anthropogenic impacts associated with the production of copra, the dried endosperm of coconuts

(*Cocos nucifera* L.) from which coconut oil is extracted. As in other regions of palm cropping, coconut plantations on Pacific atolls have profoundly altered ecological [11], hydrological [12], and geomorphological processes [13]. But beyond local accounts of coconut plantations, we know little about their present distribution on the Pacific atolls, obscuring the basin-wide scale of their environmental impacts.

More than any other plant, the coconut palm is deeply ingrained in island communities as an essential resource and a cornerstone of cultural practice [14–16]. While Indigenous peoples have propagated and cultivated coconut on Pacific islands for millennia [17], the commodification of coconut products during the colonial period transformed localized mixed cropping stands into island-wide monodominant plantations supplying Western markets [16, 18–20]. As colonial influences spread throughout the Pacific over the past two centuries, the induction of Pacific islands into the global coconut oil market caused a rapid proliferation of plantations [16, 20–23], many of which have since been abandoned due to unfavorable market conditions [16, 24, 25].

On atolls—targeted by copra producers for their flat terrain, lack of weeds, and high coconut productivity relative to volcanic islands [26]—intensified coconut cultivation was mostly realized by clearing and burning, devastating local wildlife [19, 22]. Replacement of original atoll broadleaf forests by coconut monocrops has been linked to decreased seabird abundance [27–32], soil nutrient depletion [11, 21, 27, 33], simplified food chains [11, 34], increased coastal erosion and saltwater inundation during storms [13, 35, 36], heightened competition for groundwater [12, 37], and declines in marine productivity on adjacent coral reefs [29]. These effects persist even in abandoned plantations, where coconut palms maintain monodominance via strong ecological feedbacks [11, 38–40]. Understanding the present extent of coconut plantations and their impacts is therefore crucial for confronting the sustainability challenges facing low tropical islands [13, 41].

While the expansion of palm crops like oil palm (*Elaeis* spp.) and coconut throughout the continental tropics has been thoroughly documented by remote sensing studies [42–44], coconut plantations on Pacific atolls have received only sparse treatment in the literature, and the basin-scale extent of such plantations remains unquantified. Pacific atoll forest types have never been mapped beyond individual islands or island groups [45–47], and a recent global map of coconut plantations excluded most Pacific islands due to a lack of suitable satellite imagery [44]. The Pacific atolls thus constitute one of the world's last unmapped terrestrial ecosystems, neglected in the age of satellite remote sensing due to their small sizes, remote geography, and great number.

To fill this knowledge gap, we acquired 460 very high-resolution multispectral satellite images covering nearly every atoll and geologically similar coral island (here collectively 'atolls') in the Pacific. Using a machine learning algorithm trained on the spectral and textural signatures of 45 887 training points [45], we produced vegetation maps of 235 atolls at 2 m resolution. These maps classify land areas by canopy type (coconut palm, broadleaf tree, or low vegetation) or as bare land/anthropogenic structures, allowing for the first ecoregional assessment of coconut palms on Pacific atolls.

The coconut palm is, and will continue to be, a significant part of Pacific Island cultures and economies. Here, we review the modern, post-colonial phenomenon of coconut plantations on Pacific atolls by defining their current distribution and their contribution to native habitat losses. This assessment will inform discourse on the societal trade-offs, ecological consequences, and restoration opportunities that exist today in the coconut plantations of Pacific atolls [28, 48].

## 2. Methods

### 2.1. Island selection

Atolls east of Papua New Guinea and the Philippines and west of the Americas were selected from [49], including 'atoll reefs' if vegetated land was visible in recent satellite imagery. We further extracted all 'reef islands' from [1] to capture coral islands that lack a ring shape. We treat islands that clearly share the same submerged geologic platform as a single atoll.

To ensure consistency of geologic origin, atolls and reef islands within 3 km of much larger landmasses or volcanic islands were not included because we could not verify that they lacked volcanic substrates. 183 low limestone islands (∼350 km$^2$) were excluded because they are typically composed of much older materials, sometimes augmented by volcanic inclusions [1, 50].

While some of these islands resemble the atolls targeted by this study, many feature vegetation types uncommon to atolls and would thus require an expanded classification scheme. We focus on low coral islands because of their history as targets of plantation agriculture [25], their neglect by previous coconut mapping efforts [43], and their unique exposure to climate change and related sustainability challenges [12, 40].

Featuring 266 atolls in total, our database is a highly representative inventory of Pacific atolls and coral islands. They range in size from 0.02 km$^2$ (Nukusemanu) to 367.55 km$^2$ (Kiritimati), with a median land area of 3.63 km$^2$.

### 2.2. Vegetation classification

8-band multispectral data at 2 m spatial resolution and panchromatic data at 50 cm resolution were acquired from the WorldView-2 satellite (Maxar, Inc.). Imagery was orthorectified and atmospherically corrected with AComp [51].

We prioritized recent imagery, but selected older images if they offered better coverage. Image dates ranged from December 2009 to July 2020 with a median imaging month of July 2018. Some atolls are represented by multiple mosaiced images, sometimes from several years apart.

During image acquisition, detached sandbars without visible vegetation were sometimes excluded to reduce costs. While these features are often transient and irrelevant to the present study of atoll vegetation, total land area statistics may slightly underestimate the actual area of emergent land on each atoll.

The classification scheme included four land cover types (figure 1(e)): coconut palm canopy, broadleaf tree canopy, low vegetation (grass and shrubs), and non-vegetated surfaces (anthropogenic surfaces and bare ground). The broadleaf tree class includes monocots of the genus *Pandanus*, which appear similar to broadleaf trees at 50 cm resolution. The relative consistency of tree species present on Pacific atolls allows the use of a uniform classification scheme across hundreds of distant islands [52].

The classification process and its parameters were largely derived from [45] and executed in R versions 4.0.3–4.3.1 [53]. Our classifications employed random forests, bootstrapped decision tree models that have proven among the most accurate algorithms for classifying very high-resolution imagery and have previously been applied to coconut canopies on a Pacific atoll [45, 54].

To leverage the unique shape of palm fronds, eight grey-level co-occurrence matrix (GLCM) textural features [55] were generated from each panchromatic image using 17-pixel square moving windows [45] and used alongside the eight multispectral bands of WorldView-2 as input features for the random forest models (figure S1).

Images were water masked before being classified through an iterative training process (see below) with multiple random forest models grown to 6000 trees each, as recommended by [45]. Textural features were calculated with the glcm package version 1.6.5 in R [56], and classifications were generated with the randomForest package version 4.7–1.1 [57]. More details about the classification process may be found in the supplementary material.

### 2.3. Training process

Classifying 460 satellite images with variable lighting conditions requires that training data represent the full range of visual characteristics that each class may exhibit. We found that an image's phase angle ($\theta$, see equation (1) and figure S2)—the great circle angle between the satellite and the sun from the perspective of the atoll—partially explained the visual signatures of our four classes (figure S3). We thus generated training data from images spanning the range of $\theta$ in our dataset (1.81°–75.95°) and for which clear photographic records or firsthand knowledge enabled us to accurately label training points

$$\cos\theta = \sin\delta_{\text{sun}}\sin\delta_{\text{cam}} + \cos\delta_{\text{sun}}\cos\delta_{\text{cam}} \times \cos\left(\alpha_{\text{sun}} - \alpha_{\text{cam}}\right). \quad (1)$$

In equation (1), $\delta_{\text{sun}}$ and $\alpha_{\text{sun}}$ refer to the declination and right ascension (respectively) of the sun. $\delta_{\text{cam}}$ and $\alpha_{\text{cam}}$ refer to the satellite.

Training points (∼200 per class per training image) were referenced directly to the WorldView-2 images. Trained observers haphazardly sampled each land cover type throughout the extent of the image, sampling areas near and away from class edges and featuring both heterogenous and homogenous class cover.

Because $\theta$ only partially explains the visual variability exhibited by each class across hundreds of images, we designed an iterative training and classification scheme in which all 460 images were classified with the first set of training points (27 520 points from 32 images with a wide range of $\theta$). From the 134 images that were unsatisfactorily classified in round one, a subsample was selected from which we produced the second training set (12 783 points from 16 images). From the 52 images that were unsatisfactorily classified in round two, we produced the third set of training points (5584 points from 7 images).

In each round, five classifications were produced for every image: one trained on all new points, and four trained only on points from training images with a phase angle ($\theta_t$) within 5°, 10°, 15°, or 20° of $\theta$. This process recognized that many images would be best classified with the greatest possible amount of training data, even from a wide range of $\theta_t$, but that images with atypical visual traits may be best classified by restricting $\theta_t$ to values closer to $\theta$ or by reattempting classification with a different training set in the next round. The classification results generally conformed to this prediction (table A1).

Classifications were accepted or rejected by comparing them to very high-resolution satellite imagery (both the target image and alternative imagery), aerial imagery, and other reference materials. In each round, a trained analyst evaluated the classification trained on all points before examining classifications with progressively narrower $\theta_t$ restrictions. A classification was accepted if it successfully captured large areas of homogenous land cover as well as smaller patches; for example, a closed coconut canopy should mostly be correctly identified as well as individual palms. Classifications were rejected for large


**Figure 1.** Vegetation classification of Mataiva atoll, French Polynesia. (a)–(d) Detail views demonstrating the classification of four land cover classes in homogenous, heterogenous, closed-canopy, and open-canopy contexts. Pansharpened WorldView-2 images are shown with (right) and without (left) classification overlays. (e) Ground-level images of each land cover class from various atolls. (f) Satellite image of Mataiva with locations of detail views labeled. (g) Vegetation classification of Mataiva. Satellite images © 2023 Maxar Technologies, USG Plus.

amounts of noise or random errors, even if much of the image happened to be correctly classified. While this evaluation added a subjective element to the classification process, the alternative—labeling validation points for all 460 images—was deemed infeasible (*see Discussion*).

After the third round, 28 images from 26 atolls were excluded from the study. Many featured diminished class separability due to atmospheric haze or other problems.

### 2.4. Post-processing

Clouds and their shadows were masked by hand and included as their own class where they occurred over land. The 28.2 km$^2$ of cloud-obstructed land were excluded from calculations of proportional land cover statistics but appear as a separate class in the 235 maps.

Maps were majority filtered using a 3-by-3 pixel moving window to reduce noise and aid interpretation [45]; filtering increased overall accuracy by 1.3%.

To estimate the proportion of coconut palms growing within monodominant stands, we applied a patch detection algorithm in which pixels were classified as coconut monocrop if 60% of pixels within 30 m (15 pixels) were classified as coconut canopy. We found these thresholds satisfactorily detected patches of coconut-dominated canopy while overcoming noise and bare patches between palms.

### 2.5. Validation

The accuracy of the map database was assessed using a separate set of 1969 validation pixels randomly selected from every non-cloud pixel in our database. The average density of these pixels was 1.06 $km^{-2}$ and 8.53 $atoll^{-1}$. As with the training data, validation data were labeled by a trained observer with reference materials at their disposal. Study-wide 95% confidence intervals were calculated for each class using a sample-based reference [58].

### 2.6. Climate and historical data

We obtained mean monthly rainfall data from the global precipitation measurement (GPM) integrated multi-satellite retrievals for GPM (IMERG) version 6 dataset [59] for the 0.1° pixel covering each atoll. Data are averaged from October 2000 to September 2021. GPM IMERG v6 has proven capable of accurately estimating mean monthly rainfall on a tropical atoll [60].

We investigated all 266 atolls for evidence of any history of organized copra production. English-language internet searches for the island name, 'copra,' 'coconuts,' and 'plantation' were used, and any clear reference to copra production or coconut plantations was accepted. A mix of scholarly texts, newspaper articles, and firsthand accounts was ultimately used. Sources for some atolls directly stated that no coconut cultivation had ever occurred at scale, but atolls for which no evidence could be found in either direction were classified as 'unknown.'

### 2.7. Statistical analysis

Relationships between copra history, climate, and land area were examined to isolate the role of plantation agriculture in spreading coconut palms. For island-level analyses, all 235 classifications were divided into the individual landmasses that make up each atoll. Some atolls feature a single landmass while others feature hundreds. Islands less than 100 $m^2$ were disregarded.

The effects of mean annual rainfall and land area on coconut canopy fraction were examined by fitting a linear model using the *lm* function in R 4.3.1 [53]. Data from 234 atolls (excluding Kiritimati, whose large sandbars make it a significant outlier) were used in the first model and data from the 7364 islands that comprise those 234 atolls were used in the second. For both, a full model including direct effects for rainfall and land area plus their interaction was compared to all nested models (one or both main effects and a null model) using AICc. The model containing main effects for rainfall and land area but no interaction was the most parsimonious (lowest AICc with an improvement of $\geqslant 2$ over simpler models) at the atoll scale, while the model including an interaction term was the most parsimonious at the island scale. Model discrimination plots were used to guide data transformations; both predictors were log-transformed at both scales, but coconut canopy fraction was log-transformed only at the island scale. Assumptions were verified with model criticism plots.

Linear regressions of coconut canopy fraction against copra history, land area, and mean annual rainfall were also fit using the above methodology. Land area and mean annual rainfall were both log-transformed as in the above atoll-scale model, but with copra history included as a direct effect, the most parsimonious model featured no land area effect and no interactions. Analysis of the effects of copra planting on coconut canopy fraction therefore included only rainfall as a biogeographic covariate.

## 3. Results

### 3.1. Very high-resolution vegetation maps

Vegetation maps (figure 1) reveal that coconut palms are widespread across the Pacific atolls. Maps can be viewed online in The Nature Conservancy's Geospatial Conservation Atlas (https://geospatial.tnc.org/apps/2bd5e7a72c63416ca5e137d840a0da93/) or downloaded from Dryad (https://doi.org/10.5061/dryad.0k6djhb7x) [61].

235 of 266 identified Pacific atolls were mapped, altogether covering a land area of 1925.6 $km^2$ across 8944 islands. The remaining 31 atolls could not be classified due to a lack of clear imagery. 28.2 $km^2$ of emergent land were obscured by clouds, leaving 1897.4 $km^2$ successfully classified.

Of the classified land area, coconut canopies covered 457.2 ± 21.3 $km^2$ (24.1 ± 1.1%, 95% confidence interval), broadleaf tree canopies covered 327.5 ± 22.2 $km^2$ (17.3 ± 1.2%), low vegetation covered 465.5 ± 18.6 $km^2$ (24.5 ± 1.0%), and the remaining 784.7 ± 30.8 $km^2$ (34.1 ± 0.3%) represented non-vegetated surfaces.

Validation data found the classification process highly accurate for coconut palm canopies, with a balanced accuracy of 85.3%. Balanced accuracies for broadleaf tree canopy and low vegetation were lower (75.5% and 70.3%, respectively). Non-vegetated land was classified with a balanced accuracy of 87.7%.

The 235 classification maps feature an overall accuracy of 71.1 ± 2.0%, significantly higher than the no-information rate of 34.4% ($p < 2.2 \times 10^{-16}$). Detailed accuracy statistics are provided in tables A2 and A3.

### 3.2. Coconut palms dominate Pacific atoll vegetation

The prevalence of coconut palms varied widely across atolls, island groups, and nations (figures 2 and 3). Groups with relatively high coconut canopy fractions on their atolls include Tokelau (73.1%), the Solomon Islands (66.2%) the Cook Islands (60.0%), Tuvalu

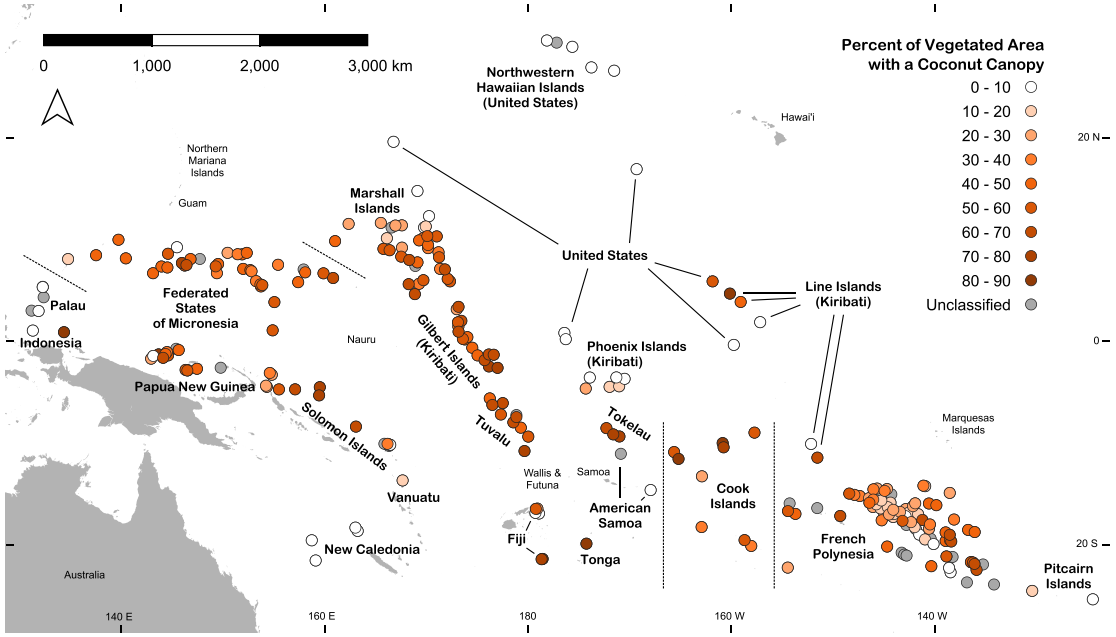


**Figure 2.** Locations of the 266 Pacific atolls, colored according to coconut canopy fraction (the percent of vegetated land classified as coconut canopy). Gray dots represent atolls that were not successfully classified. Bolded countries include at least one atoll.

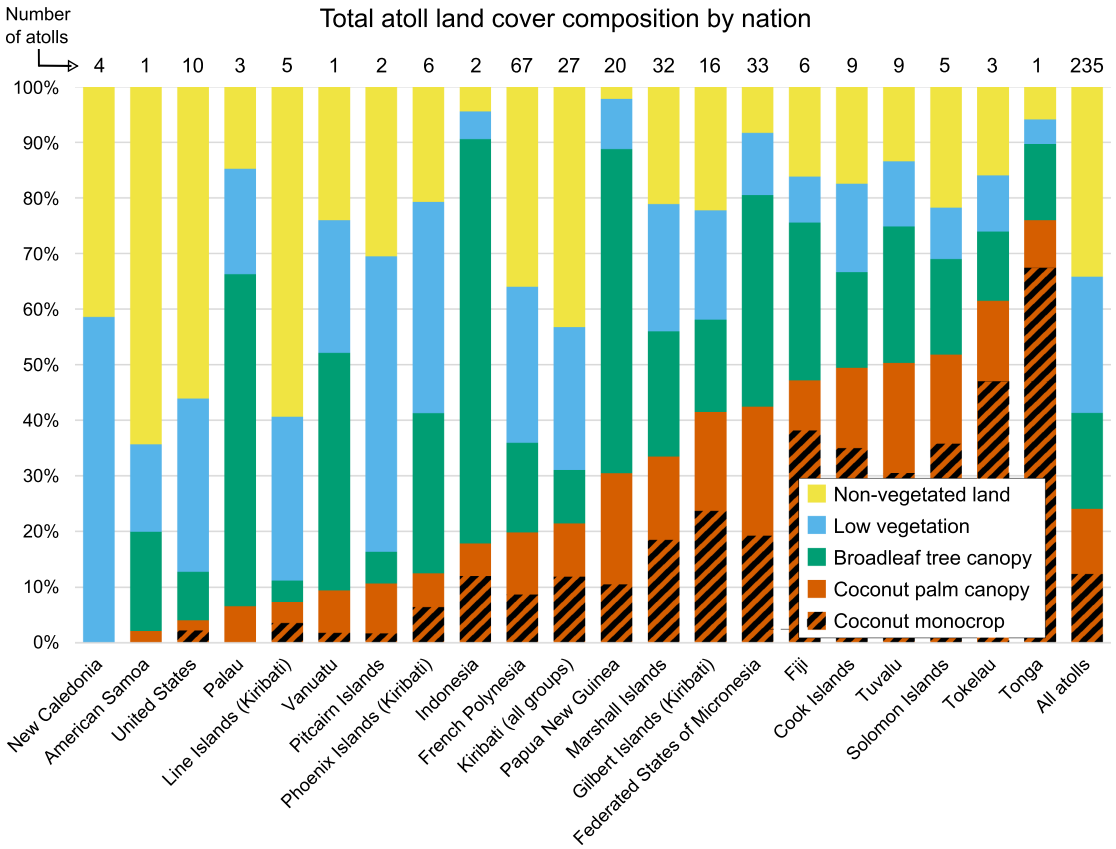


**Figure 3.** Total land cover composition of Pacific atolls by nation. Columns are sorted from lowest to highest proportional area of coconut palm. The rightmost column shows the total land cover composition of all 235 atolls. Numbers above bars display the number of atolls included. Kiribati's 27 atolls are shown aggregated ('all groups') as well as in each of the nation's three separate island groups. Coconut palms within areas of monodominance are striped.

(58.2%), and Fiji (56.3%). Some island groups support relatively small coconut canopy fractions on their atolls, such as New Caledonia (<0.1%) and the Phoenix Islands of Kiribati (15.8%).

Across 235 mapped atolls, 36.6 ± 1.0% of vegetated surfaces featured a coconut palm canopy (we refer to this metric as an atoll or island's coconut canopy fraction). By area, 58.3 ± 1.8% of tree canopies (i.e. excluding low-statured vegetation) were coconut palm. 310.9 $km^2$ of dense, monodominant coconut stands were identified across the 235 mapped atolls, representing 51.2% of the study-wide coconut canopy area.

### 3.3. Biogeographic and historical drivers of coconut palm dominance

Wetter and larger islands support more coconut palms than drier and smaller islands. Atolls receiving less than 1300 mm $yr^{-1}$ all feature coconut canopy fractions below 50.0%, with a mean of 12.0% (figure 4(a)). While mean annual rainfall affects coconut canopy fraction, its effect is modulated by landmass size (figure 4(b)). Islands smaller than 1 ha (0.01 $km^2$) support few coconuts; above this threshold, rainfall strongly influences coconut canopy fraction. The relationships between land area, rainfall, and coconut canopy fraction are statistically significant at both island (multiple linear regression, $R^2 = 0.60$, $p < 1 \times 10^{-15}$) and atoll scales ($R^2 = 0.26$, $p < 1 \times 10^{-15}$).

Atolls with histories of industrial copra production ($n = 187$) feature greater median coconut canopy fractions (43.7%) than those with no (0.1%, $n = 13$) or unknown (19.6%, $n = 66$) histories of copra production (figure 5).

Linear regressions of coconut canopy fraction against mean annual rainfall reveal similar slopes for atolls with and without histories of copra production (rainfall*history interaction term $p = 0.294$), but significantly different intercepts, with historically copra-producing atolls featuring coconut canopy fractions 32.1 percentage points greater on average across rainfall levels ($p = 1.43 \times 10^{-7}$). These analyses suggest biogeographic and historical factors both contribute to modern patterns of coconut palm dominance, but that copra production led to higher coconut canopy fractions even after accounting for the climatic favorability of islands targeted for planting.

## 4. Discussion

### 4.1. The proliferation and persistence of coconut plantations on Pacific atolls

Atolls were extensively targeted for coconut plantation development in the Pacific [18–23, 26], yet the basin-wide footprint of this land cover conversion has remained unknown. This knowledge gap presents a major obstacle to assessing the state of the Pacific's coral island ecosystems, which are a critical source of nutrients and habitat for avian, terrestrial, and marine species [2–9]. Our analysis reveals for the first time the vast legacy of colonial copra production across nearly every Pacific atoll.

Modern vegetation maps cannot reveal the natural, pre-human distribution of coconut palms on Pacific atolls. But biogeographic analyses and historical sources provide strong evidence that the coconut palm's present dominance is the outcome of two centuries of colonial plantation agriculture, not just its natural dispersal capacity or subsistence farming by ancient Pacific societies [18–20].

We find that a history of intensive copra production increases an atoll's present-day coconut canopy fraction by an average of 32.1 percentage points across rainfall levels. Leveraging our large dataset of atolls with mixed plantation histories and varied climates, this analysis models the expected coconut canopy fraction of atolls in a given climate with and without copra production. The statistically significant plantation history effect implies that plantations are associated with coconut canopy areas exceeding precolonial levels, probably at the expense of other vegetation types.

This finding corroborates numerous historical reports noting the relative scarcity of coconuts in the early period of Western contact and the subsequent clearing of broadleaf forests for coconut planting [21–23, 31, 62–64]. One account of the Pacific copra trade estimates the number of coconut palms in the region increased 60–100-fold between 1800 and 1930 [19].

The enduring importance of historical copra production is enabled by the resilience of coconut monocultures, which today represent over half of Pacific atolls' coconut canopies: even on atolls where planting and harvesting ceased decades ago, former coconut plantations persist and exclude competing vegetation [11, 38–40], leaving coconut monocultures as a stable vegetation class in the absence of human intervention [48].

### 4.2. Coconut plantations drastically alter atoll ecosystems

Coconut plantations on Pacific atolls replaced mostly broadleaf vegetation communities (figure 1(e)) dominated by native broadleaf canopy trees *Pisonia grandis* R.Br., *Barringtonia asiatica* (L.) Kurz, *Heliotropium arboreum* (Blanco) Mabb., *Cordia subcordata* Lam., *Ochrosia oppositifolia* (Lam.) K.Schum, and others, with various ferns, shrubs, and *Pandanus* monocots occurring in understories and coastal fringes [22, 63, 64]. *Pisonia* forest in particular was probably once the most common climax tree canopy on Pacific atolls [22], but like other native broadleaf species, it is now confined to rare remnant stands [30, 65].

In light of their foundational role in atoll ecosystem processes, the loss of these native plants has induced profound ecological consequences. Effects

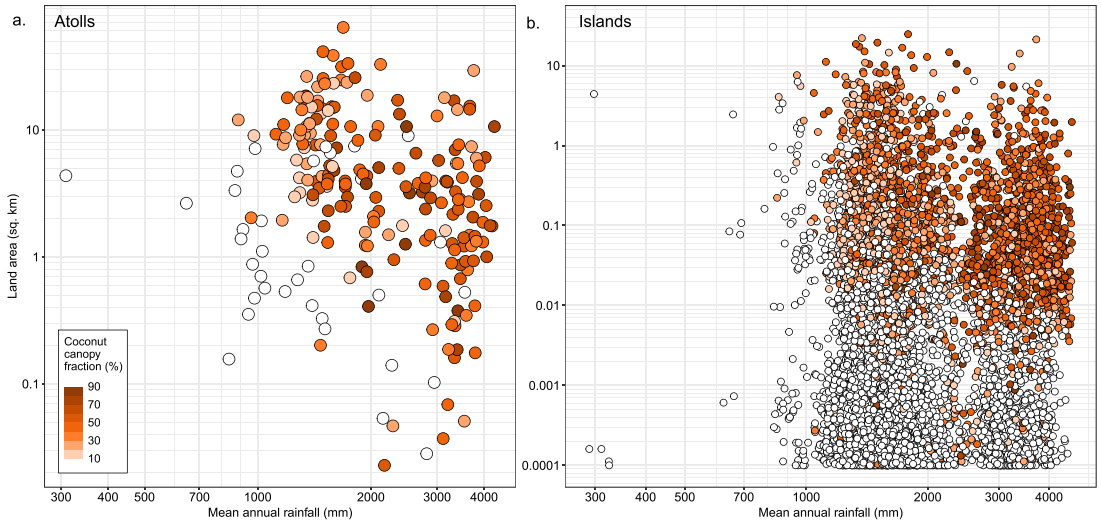


**Figure 4.** Coconut canopy fractions versus island size and rainfall. (a) Coconut canopy fractions for 234 Pacific atolls (excluding Kiritimati) versus total land area (km$^2$) and mean annual rainfall (mm yr$^{-1}$). Both independent variables are log-transformed. (b) Same as (a), but for 7364 individual islands (points are horizontally jittered).

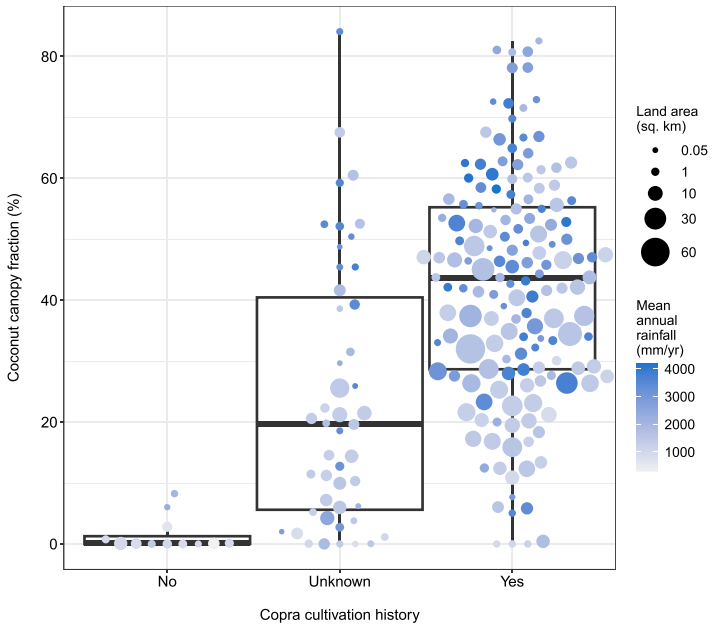


**Figure 5.** Coconut canopy fractions by copra cultivation history. Coconut canopy fractions, mean annual rainfall rates (mm yr$^{-1}$), and total land areas (km$^2$) of 234 Pacific atolls (excluding Kiritimati) grouped by historical evidence of copra cultivation.

of coconut monocropping on soil development are particularly well-studied: seabird guano helps form rich phosphate soils with high water retention atop otherwise infertile coral sands and cobbles [22, 64, 65]. On atolls, tree-nesting seabirds prefer branching broadleaf canopies over coconut palms by a factor of 8–10 [27, 28]. Coconut monocultures thus fail to produce the rich soils upon which many atoll species rely [11, 21, 22, 27, 33, 66, 67]. This loss of nutrient inputs can be exacerbated by the export of copra from coconut plantations [21, 64, 65]—one metric ton of exported copra equals a loss of over 5 kg of phosphorus [22, 68], and a large atoll can export well over a thousand metric tons of copra annually [69].

In addition to impacts on atoll soil development, the conversion of broadleaf atoll forests to coconut plantations drastically alters islands' ecological networks [11]: primary productivity decreases [11, 70], invertebrate community composition changes dramatically [34, 70, 71], predator body sizes decrease [34, 70], mammal-hosted parasites become more abundant [72], and food chains simplify [70, 71].

Ecological effects even reach into marine environments: decreased nitrogen content in runoff, increased nearshore dissolved organic carbon, and lower zooplankton and marine megafauna abundance have been linked to abandoned coconut plantations on Palmyra Atoll [29, 67]. Recent studies from atolls in the Chagos Archipelago have also demonstrated that seabird-derived nutrients—less available offshore of coconut-dominated islands—enhance coral reef productivity, algal growth, reef fish abundance, and coral resilience to ocean warming events [73–75].

Given the importance of nearshore fisheries to island residents [41], the role of reef-building organisms in building and sustaining atoll landforms [13, 76], and the value of remote islands as foci of nutrients and shallow habitat scattered amongst an immense pelagic ecosystem [3, 6–9], the potential for coconut plantations to endanger marine ecosystem processes must be re-evaluated at large scales that reflect their full extent across the Pacific basin.

### 4.3. Impacts on atoll water resources and landforms

The literature has neglected the dangers that coconut plantations pose to atoll groundwater resources. Coconut canopy fractions on Pacific atolls correlate significantly with land area and mean annual rainfall (figure 4). While larger landmasses may have attracted more coconut planters for logistical reasons, they also compensate for low rainfall by accumulating larger groundwater reserves less vulnerable to depletion [77]. Inversely, smaller islands with minimal groundwater resources can support more coconut palms if a wet climate provides frequent influxes of fresh water [22]. These trends demonstrate coconut palms' strong reliance (and influence) on atolls' limited groundwater resources [12, 78].

As these freshwater resources are increasingly vulnerable to depletion [37, 41], the water consumption of coconut plantations warrants critical evaluation. Coconut can consume 93–160 l $d^{-1}$ per palm [79] while the once-widespread canopy tree *Pisonia grandis* consumes only 14–68 l $d^{-1}$ per tree [12]. Coconut plantations, especially unmanaged ones, also often contain higher tree densities [33], which would further multiply water losses to transpiration. Coconut plantations probably deplete groundwater at a faster rate than the native vegetation they replaced, and their immense spatial footprint indicates they pose a systemic and major risk to water resources.

Some accounts suggest coconut plantations also exacerbate the erosion of atoll islands by storms and rising sea levels. Coconut plantations, especially cleared ones with minimal undergrowth, may reduce atolls' capacity to accrete sediments and withstand erosion from intense storms, rendering their islands more susceptible to climate change [13, 16, 80, 81]. Our maps will provide critical data to quantify the effects of land cover on coral island stability.

### 4.4. The future of the Pacific's coconut plantations

While coconut plantations have profoundly changed atoll ecosystems, our findings highlight their untapped potential for ecosystem restoration, resource conservation, and climate resilience.

Unlike many modern examples of deforestation for agricultural production, coconut plantations on Pacific atolls are no longer expanding at a significant rate [24]. Exports of coconut products remain economically vital to some Pacific atoll communities, but crude coconut oil and copra markets have become increasingly inaccessible to Oceania in recent years—large growers in the Philippines, Indonesia, and India together produce approximately 25 times as much copra as the Pacific Island nations combined, and shipping copra from small-scale growers on atolls to processors in Europe and Asia is challenging [24]. The infrastructure and technology needed to connect atolls to expanding domestic and global markets for coconut water, milk, virgin oil, and timber also remain underdeveloped [16, 24].

For the past 50 yr, these unfavorable market conditions have discouraged plantation upkeep and left many formerly productive atolls with vast tracts of unprofitable, aging palms [16, 24, 25]. Addressing these abandoned plantations presents an opportunity to restore native broadleaf forests and conserve essential water resources.

On atolls with active coconut plantations, diversified agroforestry approaches could allow cultivators to produce coconuts while receiving the ecological benefits of broadleaf canopy trees. One study found that if broadleaf forests, shrublands, and grasslands cover 55% of a coral island, critical seabird-driven ecosystem functions such as nutrient delivery fully recover after the eradication of invasive rats [28]. Across our study area, 64.8 $km^2$ of coconut palm on 929 islands would require conversion to broadleaf habitats to reach this threshold (see supplementary material). Paired with invasive predator eradication, this 55% reforestation threshold could serve as a target for island managers seeking to mitigate water and nutrient deficits.

### 4.5. Novel classification process for noncontiguous, high-resolution imagery

We applied a random forest classifier to a database of 460 WorldView-2 images with minimal or no overlap. The lack of overlap in the imagery confounded most existing methods to normalize very high-resolution images [82], so we developed a novel, iterative training process to leverage the explanatory power of image phase angles ($\theta$, figures S1−3). The use of $\theta$

enabled training data from a subset of images to be applied to the entire database, greatly reducing the amount of training points needed.

To avoid creating large validation datasets for all 460 images, each image's classifications were visually assessed for unacceptable noise or bias. This protocol introduced a degree of subjectivity into the process—a compromise necessary to avoid labeling tens of thousands of additional validation points, many on islands for which no reference materials were available.

The final validation was based on a labeled simple random sample of pixels from all 235 atolls and can be considered a more objective, if less granular, means of assessing accuracy. The validation data indicate that the accepted classifications achieved an overall accuracy of 71.1% after majority filtering—much lower than the 97.0% overall accuracy achieved by [45] using the same classifier on a single image, highlighting the difficulties of extending supervised classifications from one image to many. Nonetheless, the classifications show great utility for mapping coconut palm canopies, which were classified with an 85.3% balanced accuracy (table A3).

The classifications' overall accuracy was depressed in large part by the low vegetation class, which was correctly classified only 51.6% of the time (tables A2 and A3). Low vegetation is sometimes difficult to distinguish from broadleaf trees and often occupies transitional spaces between other land cover types, leading to frequent misclassification.

Classification accuracy may be improved by adopting more sophisticated deep learning methods [83], but the computational requirements of these approaches can be prohibitive for large, very high-resolution datasets. Greater accuracy may also be achieved by tuning the model design and parameters—for instance, the optimal input feature set may vary with $\theta$—or by using biogeographical variables as input features.

## 5. Conclusions

Planting by colonial enterprises transformed the coconut palm from a revered subsistence crop to a monodominant export crop on Pacific atolls. Coconut palms now represent over half of the tree cover on these low islands, while formerly widespread broadleaf trees are confined to minor fragments of their natural extent. This loss of unique atoll ecosystems exceeds even oil palm-driven deforestation in relative terms—for instance, 10.8% of Borneo's land area had been converted to oil palm monocrops in 2015 [42]—yet atoll forest conversion has scarcely received a fraction of the scholarly attention devoted to mapping oil palm-driven forest conversion. This pervasive land cover change has profoundly altered ecological and hydrological resources, potentially affecting atoll communities' resilience to climate change.

Vegetation maps will allow Pacific atoll communities to assess their forests' potential for coconut production, broadleaf forest restoration, or any path in between. Ecosystem management projects, including the conversion of abandoned coconut plantations to native forests [48] and the restoration of seabird colonies [84], have shown great promise on atolls. Yet these are invariably multi-year endeavors, and such efforts must be pursued with urgency to achieve resilience in the face of accelerating climate impacts. With these maps, we hope to assist atoll communities in charting their own futures in an era of global change.

## Data availability statement

Vegetation maps can be viewed online on The Nature Conservancy's Geospatial Atlas (https://geospatial.tnc.org/apps/2bd5e7a72c63416ca5e137d840a0da93/).

The data that support the findings of this study are openly available at the following URL/DOI: (https://doi.org/10.5061/dryad.0k6djhb7x). Data will be available from 30 November 2024.

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## Conflict of interest

The authors declare no conflicts of interest.

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# Appendix

**Table A1.** Successful classifications for each $\theta$ bin by training round. The number of images unsuccessfully classified in each round is reported under the 'none' $\theta$ bin. Results from all rounds are aggregated in the rightmost column.

| Round 1 | | Round 2 | | Round 3 | | All rounds | |
|---|---|---|---|---|---|---|---|
| $\pm\theta$ | Images classified | $\pm\theta$ | Images classified | $\pm\theta$ | Images classified | $\pm\theta$ | Images classified |
| 5 | 70 | 5 | 17 | 5 | 6 | 5 | 93 |
| 10 | 24 | 10 | 4 | 10 | 2 | 10 | 30 |
| 15 | 9 | 15 | 2 | 15 | 1 | 15 | 12 |
| 20 | 20 | 20 | 8 | 20 | 2 | 20 | 30 |
| 90 | 203 | 90 | 54 | 90 | 10 | 90 | 267 |
| None | 134 | None | 49 | None | 28 | None | 28 |

**Table A2.** Confusion matrix constructed from 1,969 independent validation points spanning all study atolls.

| | Reference: | | | | |
|---|---|---|---|---|---|
| Classification: | Coconut canopy | Broadleaf tree canopy | Low vegetation | Non-vegetated land | Total |
| Coconut canopy | 390 | 104 | 66 | 8 | 568 |
| Broadleaf tree canopy | 52 | 214 | 76 | 7 | 349 |
| Low vegetation | 21 | 41 | 237 | 104 | 403 |
| Non-vegetated land | 10 | 1 | 80 | 558 | 649 |
| Total | 473 | 360 | 459 | 677 | 1,969 |

**Table A3.** Study-wide accuracy statistics for each class.

| Statistic | Coconut canopy | Broadleaf tree canopy | Low vegetation | Non-vegetated land |
|---|---|---|---|---|
| Sensitivity (Producer's Accuracy) | 0.8245 | 0.5944 | 0.5163 | 0.8242 |
| Specificity | 0.881 | 0.9161 | 0.8901 | 0.9296 |
| Positive predictive value (User's Accuracy) | 0.6866 | 0.6132 | 0.5881 | 0.8598 |
| Negative predictive value | 0.9408 | 0.9099 | 0.8582 | 0.9098 |
| Prevalence | 0.2402 | 0.1828 | 0.2331 | 0.3438 |
| Detection rate | 0.1981 | 0.1087 | 0.1204 | 0.2834 |
| Detection prevalence | 0.2885 | 0.1772 | 0.2047 | 0.3296 |
| Balanced accuracy | 0.8528 | 0.7553 | 0.7032 | 0.8769 |

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