Original article

Crop productivity, yield and seasonality of breadfruit (*Artocarpus* spp., Moraceae)

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Crop productivity, yield and seasonality of breadfruit (*Artocarpus* spp., Moraceae).

Abstract – Introduction. Breadfruit, *Artocarpus* spp., is a staple crop with the potential to alleviate hunger and increase food security in tropical regions. Guidelines and recommendations for cultivar selection and production practices are now required for establishment of breadfruit in new areas. **Materials and methods**. To respond to this need for spreading breadfruit, our study quantified the growth, development, yield and seasonality of 24 breadfruit cultivars (26 trees) established in Kauai, Hawaii, over a 7-year period from 2006–2012. Individual production profiles were generated for each accessioned cultivar based on major agricultural factors. **Results**. Across all cultivars of breadfruit (*A. altilis*), an average of 269 fruits per year was produced by each tree with an average fruit weight of 1.2 kg. Based on the planting density of 50 trees·ha^{-1}, this translates to an average projected yield of 5.23 t·ha^{-1} after 7 years. Hybrids (*A. altilis* × *A. mariannensis*) had a higher yield than breadfruit. The data of our article support the previously proposed hypothesis for predicting breadfruit seasonality. On average, the peak season occurred from July to November. **Conclusions**. Ma'afala, the first widely available commercial cultivar, started to bear fruit within 22 to 23 months of planting. Other cultivars with potential for commercial production include Toneno, White, Rotuma and Meinpadahk.

Hawaii / *Artocarpus* / fruits / breadfruit / variety trials / choice of species / crop yield / seasonality / adaptation

Productivité de la culture, rendement et saisonnalité de l'arbre à pain (*Artocarpus* spp., Moraceae).

Résumé – Introduction. L'arbre à pain, *Artocarpus* spp., est une culture de base apte réduire la faim et améliorer la sécurité alimentaire dans les régions tropicales. Des directives et des recommandations visant la sélection variétale et les techniques de production sont maintenant nécessaires pour établir l'arbre à pain dans de nouvelles régions. **Matériel et méthodes**. Pour répondre à ce besoin d'étendre la culture de l'arbre à pain, la croissance, le développement, le rendement et la saisonnalité de 24 cultivars d'arbre à pain (26 arbres) établis à Kauai, Hawaï, ont été étudiés sur 7 ans, de 2006 à 2012. Les profils de production individuelle ont été générés pour chacun des cultivars étudiés en se basant sur les principaux paramètres de production. **Résultats**. L'ensemble de tous les cultivars d'arbre à pain de l'espèce *A. altilis* a produit une moyenne de 269 fruits par an et par arbre avec un poids moyen des fruits de 1,2 kg. Sur la base d'une densité de plantation de 50 arbres·ha^{-1}, cela se traduirait par un rendement moyen prévisible de 5,23 t·ha^{-1} après 7 ans. Les hybrides *A. altilis* × *A. mariannensis* ont eu un rendement supérieur. Nos résultats soutiennent l'hypothèse proposée précédemment prédisant la saisonnalité de l'arbre à pain. En moyenne, le pic de production a eu lieu de juillet à novembre. **Conclusions**. Le cultivar Ma'afala, premier cultivar commercial largement disponible, a commencé à produire 22 à 23 mois après sa plantation. Les cultivars Toneno, White, Rotuma et Meinpadahk seraient d'autres cultivars à fort potentiel pour une production commerciale.

Hawaï / *Artocarpus* / fruits / fruit à pain / essai de variété / choix des espèces / rendement des cultures / saisonnalité / adaptation

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1. Introduction

Breadfruit, *Artocarpus altilis* (Parkinson) Fosberg, has traditionally been used as a staple in the Pacific Islands for over 3000 years [1]. The plant is well adapted to many tropical climates and does especially well in the wet tropics where many other staple crops, especially grains, do not [1, 2]. In tropical areas, approximately 349 M people were suffering from hunger in 2012 [3]. Agriculture and food systems often fail to provide nutritious food and high-quality diets for local people, creating tension around food security in many tropical regions [4]. Regions suitable for breadfruit cultivation include much of Africa (234 M estimated undernourished population), South and Southeast Asia (65 M estimated undernourished population), Latin America and the Caribbean (49 M estimated undernourished population), and Oceania (1 M estimated undernourished population)[1] [3]. By 2050, the earth's population is expected to grow by more than three billion and in order to feed 9 billion people, food production must increase by 70% [4, 5].

Breadfruit has the potential to help alleviate world hunger and increase food security. A 1,000-calorie serving of breadfruit can fulfill over 100% of carbohydrate and fiber requirements, over 50% of potassium and magnesium, over 20% of protein, vitamin C, iron, calcium and phosphorus, and over 8% of vitamin B9 (folic acid) of the daily recommended dietary allowances (RDA) [1, 6–8]. Some specific cultivars are also a good source of pro-vitamin A carotenoids [9–12].

Commercial distribution of breadfruit cultivars has not been possible until recently due to difficulties in large-scale propagation and international quarantine programs. Methods for mass propagation of disease/insect-free plants through micropropagation technologies [13] and an international distribution system [6] have been established and relatively large numbers of breadfruit trees have been delivered to 25 countries in Africa, the Caribbean, Central America and the Pacific Islands [14]. Work is now under way to further develop breadfruit as an environmentally friendly, low-input and highly productive, sustainable agroforestry crop for developing countries in tropical areas [2, 14].

Increased commercialization and utilization of breadfruit will require basic research and data to select suitable germplasm and develop optimized production systems adapted to new locations [15]. It is believed that breadfruit is one of the most productive crops in the world, with estimated yields of 6 $t \cdot ha^{-1}$ on a dry weight basis in an orchard production system [16]. However, investigations of breadfruit yield are few in number and even less information is available comparing the yield of different cultivars [17, 18]. Additionally, most cultivars are highly seasonal [15, 17, 19], but seasonality studies have been limited to investigations within single locations and it is difficult to predict how they may perform in new regions [17, 18]. Since breadfruit is seasonal and highly perishable, unexpected changes in yield and/or seasonality could cause significant economic losses, wasted resources, and disrupt local food supplies. These losses may be mitigated through careful selection of cultivars to extend the season or to help plan for processing fruit into more stable products such as flour, chips or frozen fruit [2].

The objectives of the current study were to investigate and quantify differences in yield, seasonality and productivity of breadfruit in a common garden. Each cultivar is represented by only one or two individual trees in the germplasm repository since each tree requires significant space and cultivar conservation is a priority. Therefore, true cultivar-to-cultivar comparisons are not possible and only comparisons of the performance of individual cultivars over 7 years are made. Several factors, including the propagation method, length of the juvenile stage, yield, and fruit weight and size, were investigated to determine the degree of variability and identify suitable germplasm for international distribution. Breadfruit yield and seasonality were compared with previous reports [15, 18] that used

[1] Global Breadfruit Suitability - National Tropical Botanical Garden, accessed 17 March 2014, at http://bit.ly/14UiL79.

Table I.
Protocol for collection of seasonality data for breadfruit accessions by visual estimates.

Category	Description
Male flowers	Inflorescences of any size, small and just emerging from the sheath to full size
New fruit	Small fruits that have recently emerged from the leaf sheath; they are often prickly and the stigmas still protrude and remain green
Less than full–sized fruit	A wide range of fruit sizes from bigger than the new fruit, 1/2-size, up to almost full-sized
Full-sized fruit	Fruit that have reached their maximum size, but have not yet started to mature
Mature fruit	Fruit with distinctive characteristics of maturing, such as latex exudate on the skin and slight changes in skin color and texture
Ripe fruit	Fruit that are soft and ripe on the tree
Fruits with disease symptoms	Fruit with black spots or other disease symptoms evident on the peel

some of the same genetic materials planted in different locations.

2. Materials and methods

The Breadfruit Institute at the National Tropical Botanical Garden (NTBG) holds the world's largest curated germplasm collection of breadfruit and its associated relatives including *Artocarpus altilis, A. camansi, A. mariannensis* and *A. altilis* × *A. mariannensis* hybrids. The collection includes 325 well-documented trees collected from 34 Pacific Islands, the Philippines, Indonesia, Honduras and the Seychelles between 1978 and 2004 [6, 7, 11]. The majority of the trees are conserved in a single 12-acre (4.86 ha) site at Kahanu Garden in Maui (20°47'57.07" N, 156°02'18.42" W) and have been described in detail previously [11]. A subset of 26 accessions was established at the NTBG's McBryde Garden on Kauai, Hawaii (21°88'79.43" N, 159°49'23.15" W). Kauai has a subtropical climate and the major rainy season usually starts in October and ends in April. The McBryde Garden receives rainfall of 939 mm annually with a mean temperature of 24.4 °C, mean maximum temperature of 29.0 °C, and mean minimum temperature of 19.7 °C[2]. The trees were planted in a grassy field in land that had been fallow since it was intensively cultivated with sugarcane until the early 1970s and the soil is compacted from this heavy use. Trees were planted 15 m apart giving a planting density of about 50 trees·ha^{-1}, irrigated as needed, and mulched and fertilized yearly with a standard N:P:K fertilizer. In 2011, a cover crop of *Lablab purpureus* was planted beneath the *A. camansi* trees. Trees were pruned and shaped as they grew, beginning with some cultivars in April 2008 and again in November 2011, with the exception of the cultivars White and Rare autia.

A standard methodology was used for all data collection (*table I*). Data were collected weekly from 2006 to 2012. Each tree was divided into four quadrants, and data were collected for each quadrant from southwest to southeast going clockwise around the tree. Using a visual assessment, male flowers and fruit in five stages of development were counted in each quadrant. Mature fruit were then harvested, weighed and measured. Fruit with any disease symptoms were counted, harvested and disposed of. Aborted fruit on the ground were counted. The total fruit number includes new fruit, less than full-sized fruit, full-sized fruit, mature fruit and ripe fruit. Edible/harvestable fruit refers to full-sized fruit, mature fruit and ripe fruit. The plant canopy area, percent leaf area and plant height were analyzed using the ImageJ 1.47v software (Natl. Inst. Mental Health, Res. Serv. Branch,

[2] WRCC (West Regional Climate Center), accessed 27 Dec 2013, at: http://wrcc.dri.edu/.

Table II.
Number of months between planting and fruit production for *Artocarpus* species and cultivars grown in the McBryde Garden, Kauai, Hawaii.

Species	Cultivar	Planted date	First fruit appear	Month	Source
A. mariannensis	Dugdug	21 Apr. 2004	18 Sept. 2007	41	Seed Mariana Islands
A. camansi	Kapiak	21 Apr. 2004	08 Dec. 2006	32	Seed Papua New Guinea
			08 Dec. 2006	32	
			19 Mar. 2007	35	
			09 Apr. 2007	36	
			19 Feb. 2007	34	
			12 Mar. 2007	35	
			05 May 2007	37	
			12 Feb. 2007	34	
			25 Nov. 2008	55	
			07 Jan. 2009	57	
A.altilis × *A. mariannensis*	Meinpadahk	21 Apr. 2004	25 June 2007	38	Roots Kahanu Garden
		28 Apr. 2004	18 June 2007	38	
	Rotuma	28 Apr. 2004	13 May 2007	37	
	Yap		16 Apr. 2007	36	
A. altilis	Afara	03 Jan. 2006	21 May 2008	29	Roots Kahanu Garden
	Meitehid	20 June-2005	18 Sep. 2007	27	
	Otea	03 Jan. 2006	21 May 2008	29	
	Porohiti	28 Apr. 2004	18 June 2007	38	
	Rare autia	03 Jan. 2006	12 Nov. 2007	23	
	Toneno	28 Apr. 2004	16 Apr. 2007	36	
	Ulu fiti	20 June 2005	04 Oct. 2007	28	
	White	20 June-2005	24 July 2007	25	
	Ma'afala	21 Nov. 2008	02 Sept.2010	22	*In vitro*, Murch
	Ma'afala	20 Oct. 2008	13 Sept. 2010	23	

Bethesda, Maryland, USA). Tree circumference was measured at knee height (0.35 m) rather than breast height due to the branching habit of some trees.

3. Results and discussion

The wild seeded progenitor species of breadfruit, breadnut (*A. camansi*), is propagated by seed. Domesticated breadfruit, both seeded and seedless , is traditionally propagated by adventitious root shoots, root cuttings or air layering. Recently, mass propagation of breadfruit has become possible through *in vitro* micropropagation techniques [13, 20]. According to the different propagation methods, the individual germplasm produced requires a different number of months to yield fruit (*table II*). In our study, *Artocarpus altilis* grown from root cuttings started to bear fruit after an average of 29 months (*table II*), while hybrids (*A. altilis* × *A. mariannensis*) took significantly longer, with an average of 37 months. Fast-fruiting cultivars from root cuttings are Rare autia (23 months), White (25 months) and Meitehid (27 months); however, replication of individual cultivars is needed to assess the significance of these differences. Breadnut (*A. camansi*) trees grown from seed produced fruit after an average of 39 months, with a range from

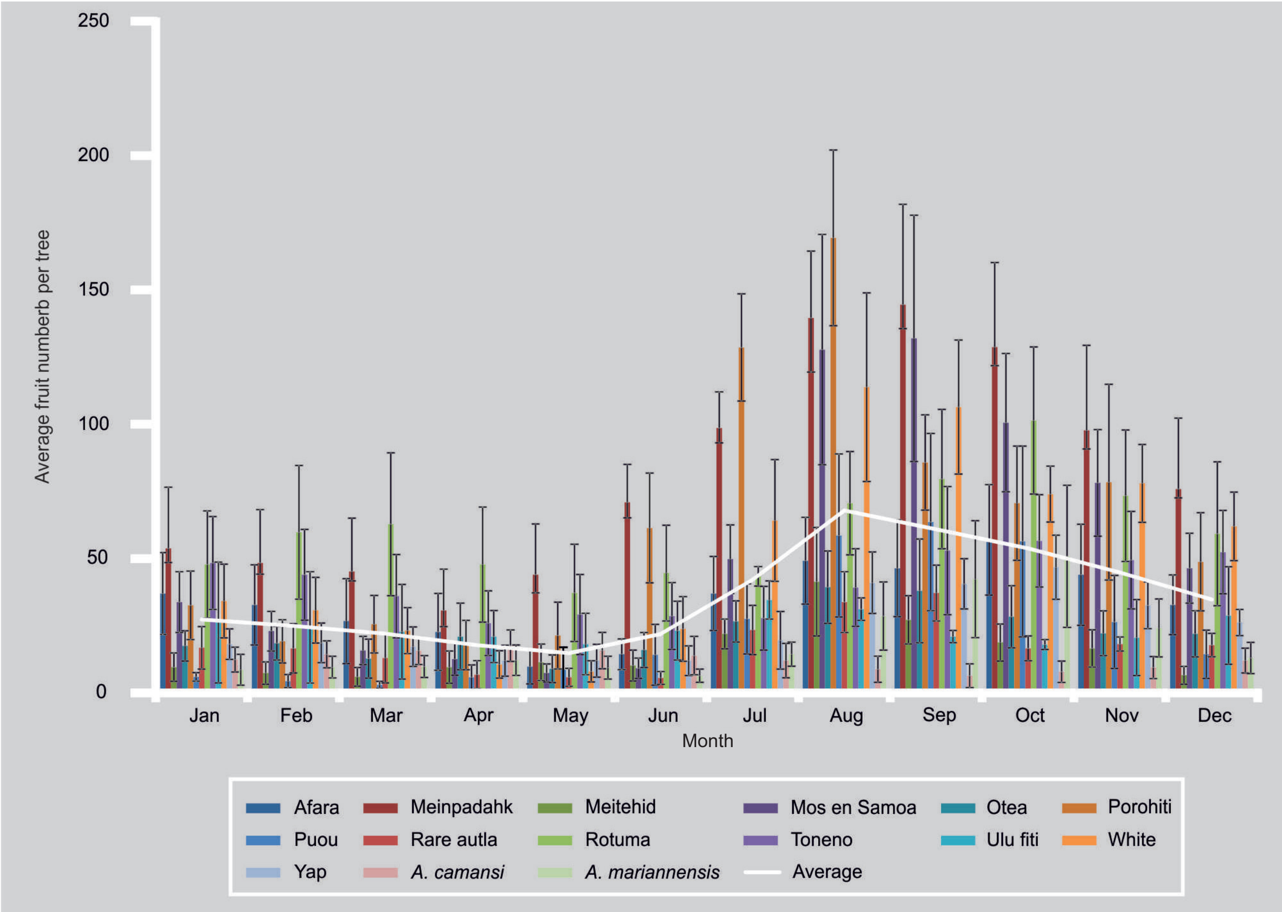

Figure 1.
Average fruit number per month of breadfruit cultivars planted from 2008 to 2012. Bars represent the standard error of the mean of each month over the 5-year data collection period. Each cultivar has one tree except for *A. camansi* (n = 10) and Meinpadahk (n = 2).
A color figure is available at www.fruits-journal.org.

(32 to 57) months. *In vitro*-propagated trees of the cultivar Ma'afala began fruiting within 23 months (*table II*). While these observations do not emphatically demonstrate differences among the methods, *in vitro* propagation has resulted in early flowering in other perennial tree crops such as Scots pine [21]. *In vitro* micropropagation has many other advantages including certified disease-free stocks, genetic consistency and higher survival rates [13, 20]. These preliminary data suggest that *in vitro* propagation may shorten the juvenile stage of breadfruit trees, resulting in more rapid maturation and earlier fruit production.

Individual breadfruit cultivars (*Artocarpus* spp.) produced fruit at different times throughout the year, with the major fruiting season from July to November (*figures 1, 2*). Monthly fruit production during the peak season was as high as 145 fruits per tree for Meinpadahk, and as low as 16 fruits for Meitehid. Some cultivars, such as Rotuma (hybrid), White (breadfruit), Toneno (breadfruit) and Mos en Samoa (breadfruit), had another small production peak during the spring (146 fruits for the entire year). Highly productive cultivars including Meinpadahk (hybrid), Rotuma (hybrid) and Mos en Samoa (breadfruit) maintained twice the average fruit production throughout the year (*figure 1*). Overall, *Artocarpus altilis* trees produced 269 fruits per year during the peak season, which was slightly less than the hybrids (*A. altilis* × *A. mariannensis*) at about 289 fruits per year (*figure 2*). Both numbers are higher than previous estimates of about 150–250 fruits per tree per year [2, 19]. On average, 64% of the fruit was produced during the peak season for breadfruit and 58% for hybrids (*figure 2*). The average fruit number (breadfruit and hybrid) during the entire year was approximately 40 fruits per month; 59 fruits per month

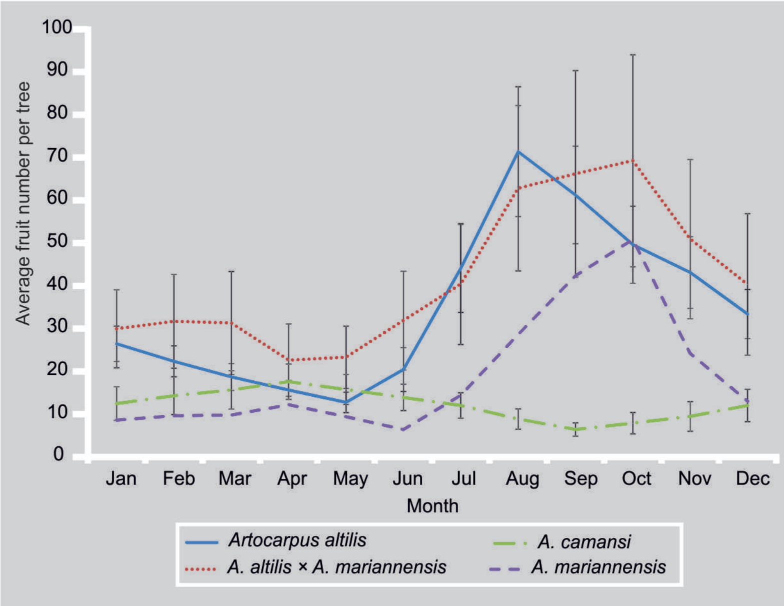

Figure 2.
Average fruit number per month of *Artocarpus altilis* (n = 10), *A. camansi* (n = 4), *A. mariannensis* (n = 1) and *A. altilis* × *A. mariannensis* (n = 10) from 2008 to 2012. Bars represent the standard error of the mean of each species over the 5-year data collection period. The fruit number was the cumulative number of fruits from the previous month and new fruits. A color figure is available at www.fruits-journal.org.

during the peak season; and 26 fruits per month during the low season. Dugdug (*A. mariannensis*) had the most distinct peak season from August to November with fruit production of 160 (70%). Seasonal differences were less obvious for breadnut (*A. camansi*) and fruit production was lower (*figure 2*).

Most of the cultivars produced fruit 4 years after planting, with an average of (47 ± 8) fruits produced by the juvenile trees. As the trees aged, the number of fruit increased to (130 ± 22) fruits per tree after 7 years and continued to increase throughout the study (*figure 3*). After 7 years, hybrids (*A. altilis* × *A. mariannensis*) produced an average of (131 ± 36) fruits per tree, while breadfruit (*A. altilis*) produced an average of (129 ± 28) fruits per tree (*table III*). For 7-year-old breadnut (*A. camansi*) trees, the total fruit production was lower at about (52 ± 9) fruits per tree, suggesting that increased fruit production was selected for during the domestication process. Hybrids produced higher yields than the other species at both 4 and 7 years after planting. Based on these 7 years of field data, most cultivars showed a linear increase in total fruit number per year after initiating fruit production. As a group, the total fruit number increased from 3 to 7 years after planting following a linear equation, $y = 27.181x - 21.428$, $R^2 = 0.9684$ (*figure 3*). The average increase in fruit number per year was about 25.0 but it varied among cultivars. Porohiti had the highest growth rate at 42.9 ($y = 42.9x - 37.8$, $R^2 = 0.9258$), followed by Meinpadahk at 42.3 ($y = 42.3x - 40.1$, $R^2 = 0.9537$), and White at 38.7 ($y = 38.7x - 30.1$, $R^2 = 0.8131$). The high R^2 values and linear relationship suggest that the yields will continue to increase in the future and the potential yields of a mature orchard may be greater than what is reported here.

The harvested fruit generally weighed between 1.0 kg and 2.0 kg during the study years depending on the cultivar (*figure 4*). The average fruit weight was 1.2 kg across cultivars. However, differences in fruit size were found among cultivars and the extent of these differences increased as the trees grew older. For 4-year-old trees, the Toneno, Rotuma, Rare autia and Otea cultivars had mean fruit weights over 1.0 kg; Afara and Mos en Samoa weighed over 0.5 kg; and Meitehid weighed less than 0.5 kg. At 7 years after planting, Yap, Toneno, Rotuma and Mos en Samoa grew heavier, with fruit over 1.5 kg; Meitehid, Meinpadahk and Rare autia weighed over 1.0 kg, while Porohiti weighed over 0.5 kg. Over this 3-year-period, Rotuma and Porohiti produced increasingly heavier fruit, with an average increase of around 0.58 kg. Most cultivars, including Meitehid, Meinpadahk, Rare autia, Mos en Samoa, Ulu fiti and White, produced fruit that increased in weight by 0.98 kg over the 3 years of production. Seven years after planting, the average fruit weight for hybrids (*A. altilis* × *A. mariannensis*) was (2.0 ± 0.63) kg, while the average weight for breadfruit (*A. altilis*) was (1.2 ± 0.15) kg (*table III*). It is notable that, seven years after planting, Yap (*A. altilis* × *A. mariannensis*) had an average fruit weight of 3.2 kg, which was twice as heavy as most cultivars and similar (2.54 kg) to what has been observed in Kahanu Garden [7].

Based on the planting density of 50 trees·ha^{-1} used in our study, the average projected yield for 4-year-old trees was

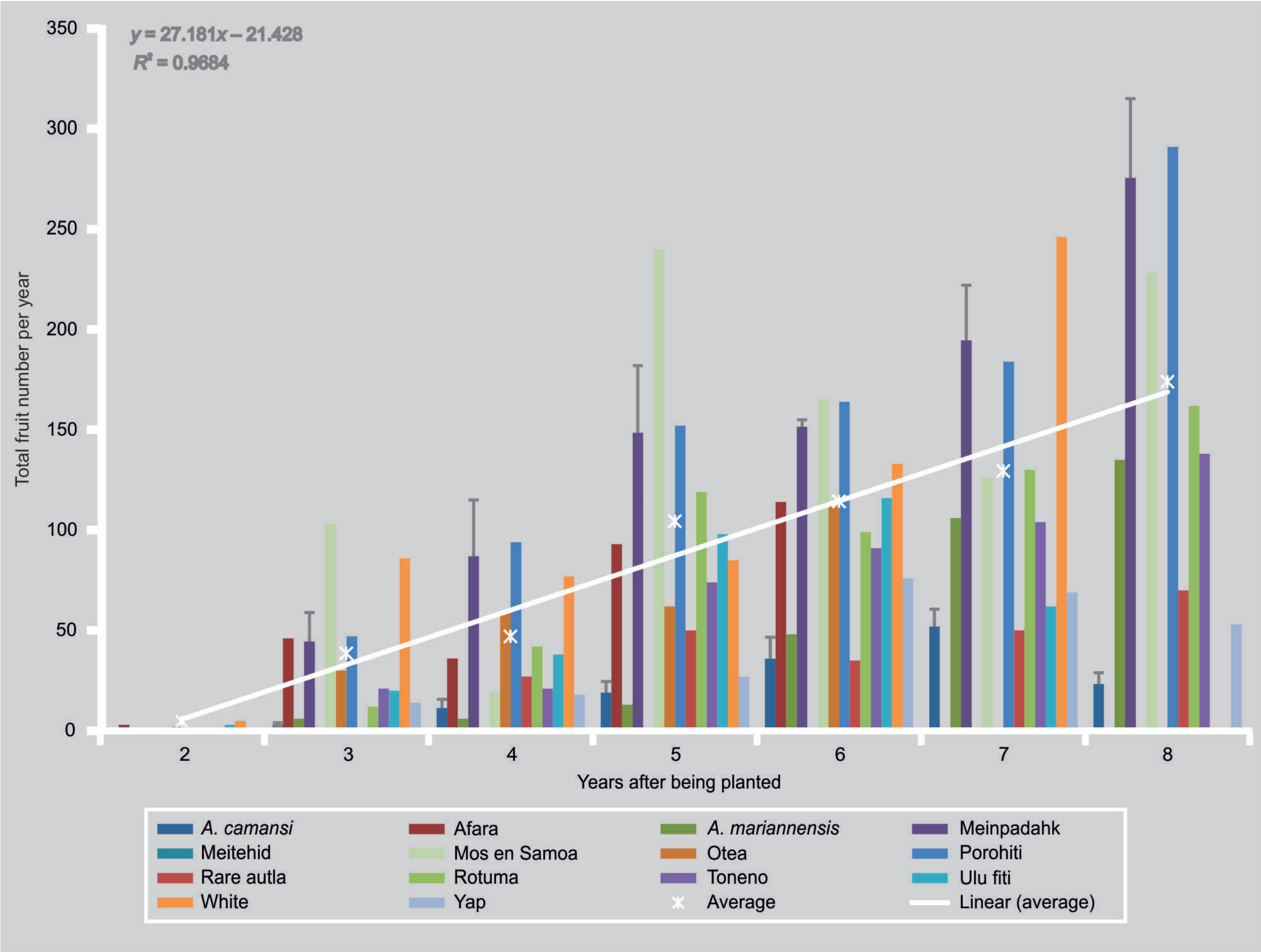

Figure 3.
Average fruit number per year of breadfruit cultivars planted in the National Tropical Botanical Garden in Kauai, Hawaii, from 2 years to 8 years old. Bars represent the standard error of the mean of individual trees. *A. camansi* (n = 10), Meinpadahk (n = 2). A color figure is available at www.fruits-journal.org.

(1.69 ± 0.27) t·ha^{-1}, with the highest yield of (2.75 ± 0.02) t·ha^{-1} for Otea and the lowest yield of (0.76 ± 0.02) t·ha^{-1} for Mos en Samoa (*figure 5*). At 7 years after planting, the projected average yield reached (6.34 ± 1.01) t·ha^{-1} but was as high as (9.37 ± 0.05) t·ha^{-1} for Meinpadahk and as low as (2.28 ± 0.04) t·ha^{-1} for Rare autia. The average annual yield for the hybrid cultivars (*A. altilis* × *A. mariannensis*) included in our study was 8.56 t·ha^{-1} after 7 years, while for breadfruit (*A. altilis*), the number was lower at 5.23 t·ha^{-1}. This compares favorably with the average global yields of rice, wheat or corn at (4.1, 2.6 and 4.0) t·ha^{-1}, respectively [22]. Based on an average fruit moisture content of about 68% [7], this translates to about 2.7 t·ha^{-1} for the hybrids and 1.7 t·ha^{-1} for breadfruit on a dry weight basis 7 years after planting. Hybrids showed an advantage in fruit number, weight and yield. Fruit drop is one of the contributing factors that limit yield. The rate of fruit drop ranged from 2% to 70% depending on the cultivar (data not shown). Given this observation, it may be beneficial to thin the fruit and/or prune the tree to encourage fruit maturation, as is commonly practiced with other tree fruits such as apple, pear, peach and cherry [23, 24].

According to our results, hybrids had the largest trunk circumference (1.07 m), while *A. mariannensis* had the smallest (0.89 m) (*table III*). Hybrids had a larger canopy area (37.90 m^2), higher percent leaf area (95.16%) and were taller (5.91 m) than breadfruit (23.26 m^2, 90.33% and 5.14 m, respectively). Breadnut (*A. camansi*) had the highest tree height at 7.61 m and the largest canopy area of 41.73 m^2; however,

Table III.
Summary of total fruit number, average fruit weight and yield on breadfruit (*Artocarpus* spp.) 4 years and 7 years after being planted. Different plant numbers exist due to differences in the planting date.

4 years after planting				
Species	Plant number	Total fruit number	Average fruit weight (g)	Yield ($t \cdot ha^{-1}$)
A. camansi	10	11 ± 4	344.00	0.19
A. mariannensis	1	6.00	–	–
A. altilis	7	45 ± 10	1181.12	1.60
A.altilis × *A. mariannensis*	4	49 ± 20	735.47	1.90

7 years after planting				
Species	Plant number	Total fruit number	Average fruit weight (g)	Yield ($t \cdot ha^{-1}$)
A. camansi	10	52 ± 9	1612.26 ± 71.70	3.35
A. mariannensis	1	106.00	563.5 ± 52.95	2.85
A. altilis	5	129 ± 28	1170.01	5.23
A.altilis × *A. mariannensis*	4	131 ± 36	2038.02	8.56

9 years after planting					
Species	Plant number	Canopy area (m^2)	% Leaf area	Perimeter (m)	Height (m)
A. camansi	10	41.73	84.30	0.91	7.61
A. mariannensis	1	32.41	96.43	0.89	5.51
A. altilis	4	23.26	90.33	0.94	5.14
A.altilis × *A. mariannensis*	4	37.90	95.16	1.07	5.91

the percent leaf area was the lowest. Based on these data, it could be concluded that heterosis may exist in *Artocarpus* hybrids. Heterosis shows a superiority in growth rate, reproductive success and yield [25]. Hybridization and introgression have been observed and applied to increase crop yields since ancient times [26]. An increase in yield ranging from 15% to 50% has been reported for maize, sorghum, rice and sunflower. Hybrids can also have advantages for pathogen-resistance traits or better adaptation to extreme climates or new light regimes [26].

Ma'afala has been the most widely distributed cultivar in recent years, with more than 30,000 trees distributed since 2007 according to the Breadfruit Institute of the National Tropical Botanical Garden[3]. In the Kahanu Garden germplasm collection on Maui, mature Ma'afala trees produced fruit most reliably from July to December [15]. Juvenile clones of this tree planted on Kauai displayed a slight delay in the first two fruiting seasons (*figure 6*). However, as the trees matured, the season became more similar to that of more established trees in Kahanu Garden on Maui, with the most fruit being produced in July of 2012 (*figure 6*). Based on this data, a slight shift in seasonality of juvenile breadfruit should be considered for agricultural applications. The flowering periods occurred (3 to 4) months earlier than the fruiting season, which is consistent with previous observations [15]. The average fruit weight of Ma'afala grown in Kauai was 576 g, with the smallest fruit measured at 425 g in May 2011 and the largest fruit measured at 886 g in September 2011 (*figure 6*). Nevertheless, based on these data, farmers could expect approximately 1.5 $t \cdot ha^{-1}$ after 3 years and

[3] NTBG (National Tropical Botanical Garden), accessed 27 Dec 2013, at http://www.ntbg.org

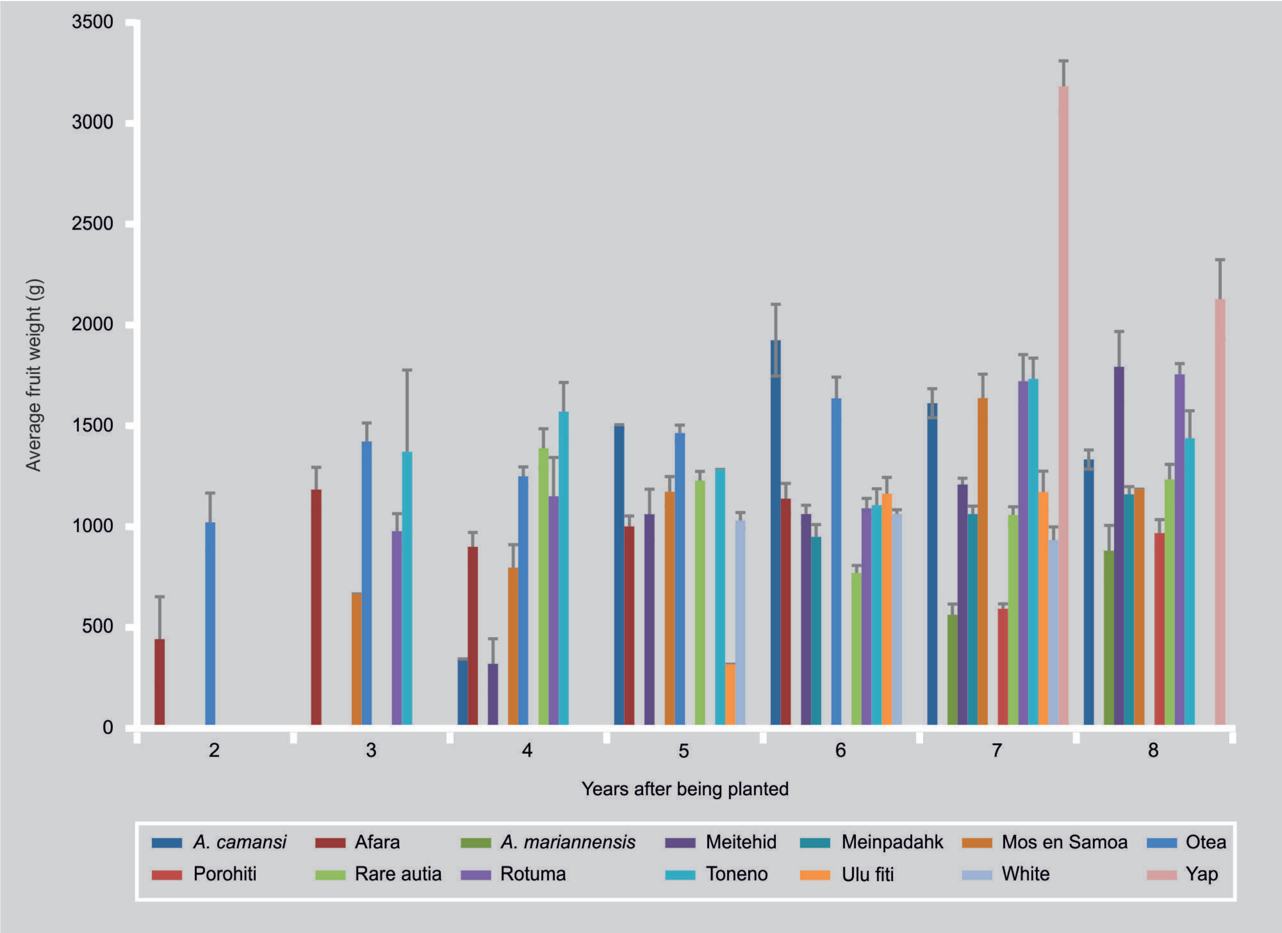

Figure 4.
Average fruit weight for breadfruit cultivars from 2 years old to 8 years old. Bars represent the standard error of the mean for fruit produced in each year. Data is unavailable for certain years in the study and a different number of fruit was measured for each tree of each variety in each year.
A color figure is available at www.fruits-journal.org.

2.7 t·ha^{-1} after 4 years at a planting density of 50 trees·ha^{-1}, demonstrating the increasing productivity of the trees over time. Based on the linear increase in yield observed for the other cultivars between 2 years and 8 years after planting (*figure 5*), Ma'afala could be expected to yield approximately 8.5 t·ha^{-1} eight years after planting.

The yield data obtained in Kauai was higher than what has been reported using the same genetic stock in New Caledonia [18] (*table IV*). In New Caledonia, Rotuma had an average fruit weight of (679 ± 123.7) g, which is less than half of that observed in Kauai [(1443 ± 65.4) g]. Likewise, fruit length was (11.7 ± 0.3) cm in New Caledonia compared with (16.4 ± 0.3) cm in Kauai. The average weight and size in Kauai was closer to what was observed in Maui, with a range of 12–16 cm × 12–15 cm and an average weight of 1.1 kg [2]. Ma'afala fruit were also about twice as large in the Kauai collection, with an average fruit weight of (609 ± 21) g compared with (300 ± 72.1) g in New Caledonia (*table IV*). Ma'afala fruit size was also significantly larger for trees grown in Kauai, with fruit measuring (12 ± 0.2) cm compared with (9.0 ± 0.9) cm in New Caledonia [18]. The average weight and size of Ma'afala fruit in Kauai was closer to previous reports in the existing literature (12–16 cm × 10–13 cm, 0.8 kg) [2]. While New Caledonia and Kauai are similar distances from the equator (*table V*), the trees planted in New Caledonia suffered from water-logging issues and a suspected problem with soil-borne diseases [18]. As such, the lower fruit sizes and productivity observed in New Caledonia are likely a result of microclimatic and biotic variables rather than the overall environment.

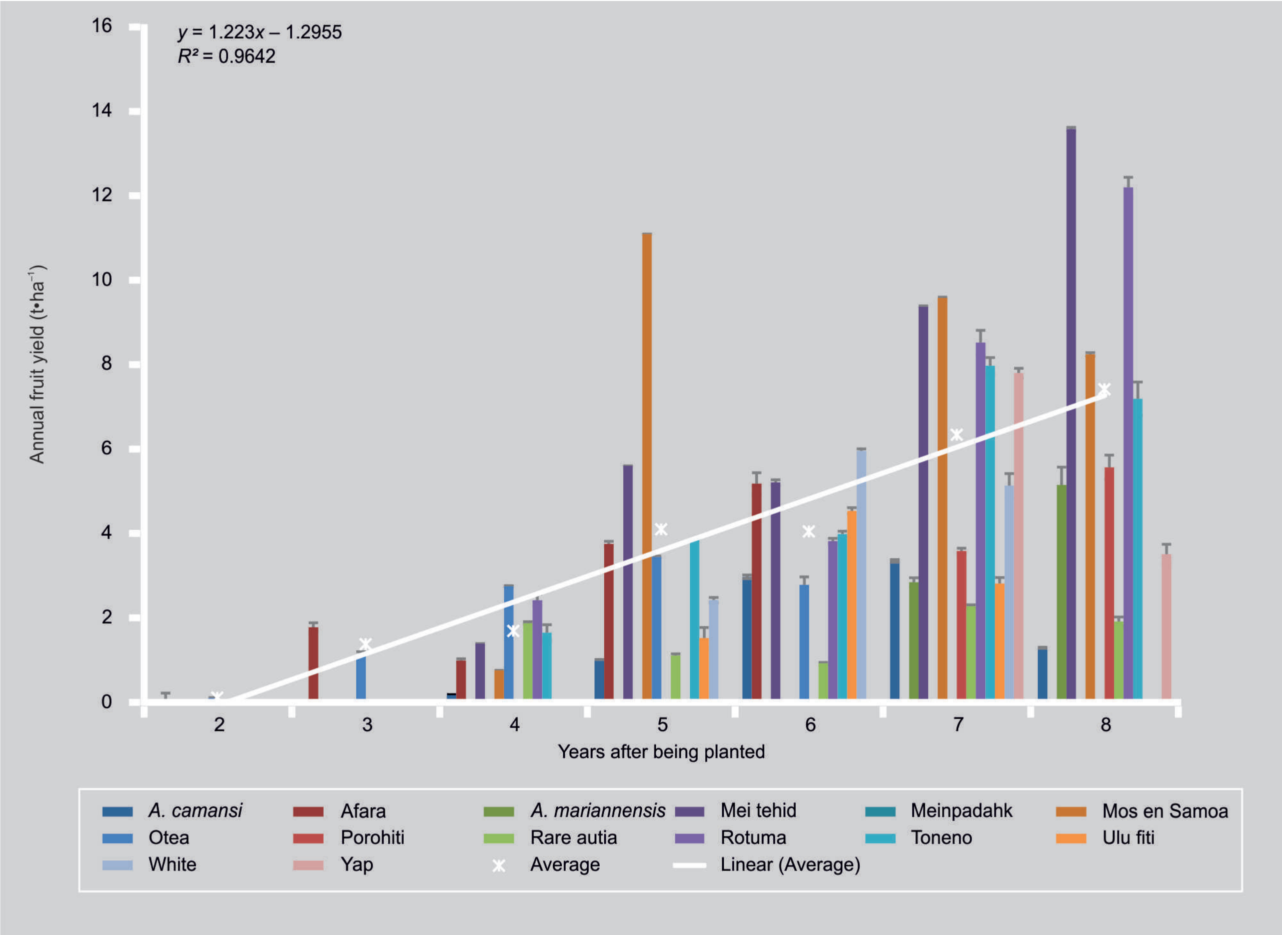

Figure 5.
Yield for breadfruit cultivars from 2 years to 8 years old. Data is unavailable for certain years in the study. Bars represent the standard error of the mean of individual trees. *A. camansi* (n = 10), Meinpadahk (n = 2). The yield was calculated as follows: [Average weight × (average total fruit number per year – aborted fruit – fruit with rots) × 50 trees]. A color figure is available at www.fruits-journal.org.

Compared with previous studies of breadnut (*A. camansi*) trees, the data obtained in Kauai showed higher variation (*table VI*). In Roberts-Nkrumah's experiment [27], three breadnut trees were grown at the University of the West Indies Field Station (UWI-FS) in Valsayn, Trinidad and Tobago (lat. 10°2' to 11°12' N, long. 60°30' to 61°56' W), which has a mean temperature of 26.8 °C and mean precipitation of 1575 mm. In her study, there were positive correlations between seed mass and seed number (r = 0.87), seed mass and fruit mass (r = 0.83), and seed number and fruit mass (r = 0.77). There was no difference between years or plant age. The fruit size and weight observed in Kauai were larger than they were in the UWI-FS for all ages. However, seed number and seed mass were lower in Kauai after 6 and 8 years than they were in the UWI-FS. These comparisons indicate that the positive correlations found in Roberts-Nkrumah's study may not apply when comparing data between her study and our study (*table VI*). In Kauai, breadnut had a higher seed weight than at the UWI-FS. Breadnut in Kauai had a lower percentage of seed mass per fruit at all ages. Seed mass from both locations were lower than 50% of the fruit. Fruit and seed production per tree varied dramatically from year to year (30 kg to 140 kg, 10 kg to 60 kg, respectively). Trees in Kauai were grown from seeds collected from the wild and cultivated trees in Papua New Guinea, the center of origin for this species, while the ones at the UWI-FS were likely from a single seed source. Variation in fruit and seed production between individuals was found in Kauai.

As previously reported, there does not appear to be an influence of precipitation patterns on seasonality in breadfruit [28]. In terms of seasons for harvestable fruits - full size, mature and/or ripe (*figure 7*), most cultivars, including Afara, Otea, Meinpadahk, Porohiti, Meitehid, Ulu fiti and Yap, bore edible fruit at similar times in Kauai and Maui. The likelihood of bearing fruit was lower in Kauai compared with Maui, with the exception of Meitehid and Ulu fiti. However, the current study is based on fewer years of data and was collected from younger trees that may have less consistent fruiting patterns. Meitehid had a longer low season in Kauai, that lasted from April to August. Ulu fiti maintained the same seasonality as well as the same likelihood of fruiting in Kauai and Maui. Yap tended to be less seasonal than most cultivars and it kept this attribute when it was planted in Kauai. Puou and White shared similar seasonality in Kauai and Maui, with a 2-month delay in the onset of the low season in Kauai. Rotuma and Toneno displayed different seasonality profiles in Kauai than in Maui. In Maui, Rotuma has a distinct season between November and February and a low season between April and August. However, when it was planted in Kauai, Rotuma produced fruit much more sporadically and was less seasonal. Fruit production occurred in only two years and it is possible that Rotuma would develop a similar profile as it matures and fruits more regularly. In Maui, Toneno has a peak season from October to January and a low season from March to July. In Kauai, the peak season shifted to May to July and the low season moved to July to September. Overall, the edible fruit season remained relatively consistent between Maui and Kauai.

Similar trends were seen for the male flower season between trees in Kauai and Maui (*figure 8*). Afara and Yap had almost the same seasonality and number of years with trees producing male flowers. Cultivars such as White, Porohiti and Meitehid shared similar seasonality in Kauai and Maui, but had a greater number of years with male flowers. Rotuma, Ulu fiti and Otea had similar seasonality but a 2- to 3-month longer peak season. Puou, Meinpadahk and Toneno experienced a 2-month delay in the flowering season in Kauai. Overall, breadfruit kept the same male flower seasonality between Kauai and Maui.

The McBryde Garden on Kauai shares a similar rainy season to the Kahanu Garden on Maui. However, the Kauai location receives about half of the annual precipitation reported for the Kahanu Garden (*table V*) [20]. The seasonality of male flowers did not vary between the two locations, indicating that the amount of precipitation is not the dominant factor in determining edible fruit/male flower seasonality. Jones *et al.* proposed a hypothesis that seasonality of breadfruit is closely related to the distance from the equator, potentially due to differences in the light quality/spectrum throughout the season [15]. In this hypothesis,

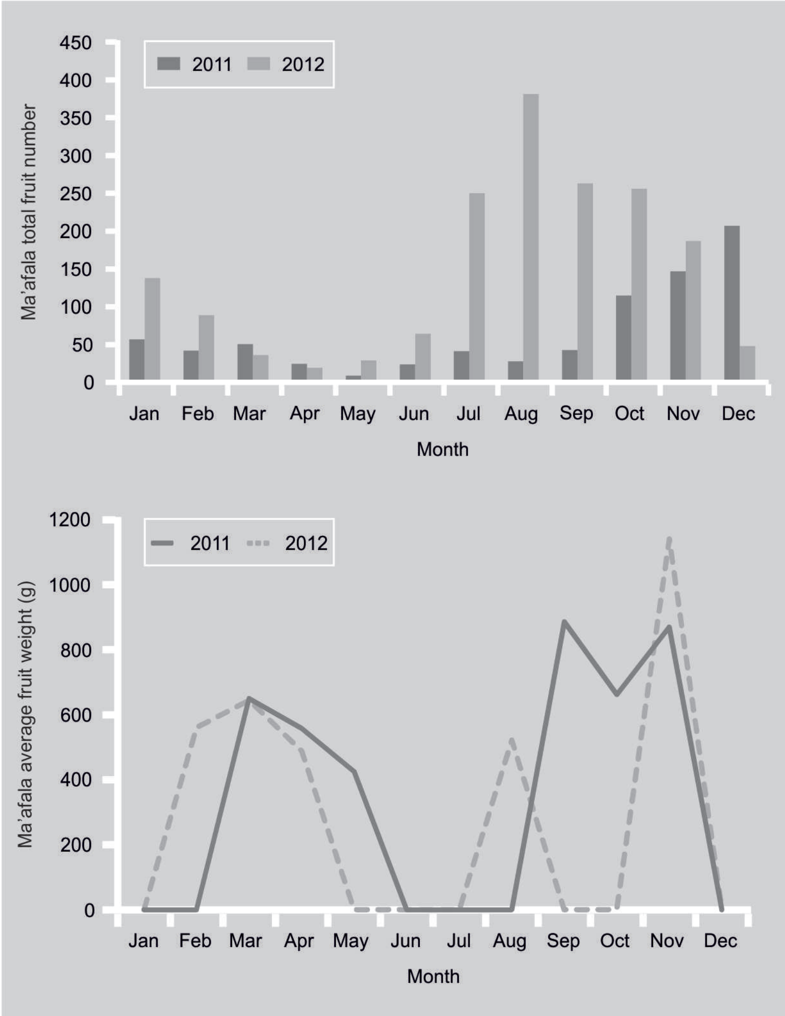

Figure 6.
Total fruit number and average fruit weight for the breadfruit cultivar Ma'afala in the National Tropical Botanical Garden in Kauai, Hawaii. The number is an average of two trees planted in the garden in 2011 and 2012.

Table IV.
Comparison of fruit growth between Rotuma and Ma'afala in Kauai (Hawaii) and New Caledonia [18].

Artocarpus cultivar	Location	Average fruit weight (g)	Average size (cm)
Rotuma	New Caledonia	679 ± 123.7	11.7 ± 0.3
	Kauai	1143 ± 65.4	16.4 ± 0.3
Ma'afala	New Caledonia	300 ± 72.1	9.0 ± 0.9
	Kauai	609 ± 21	12.0 ± 0.2

Table V.
Comparison of environmental and climate factors for breadfruit plantings in Kauai and Maui, Hawaii, and New Caledonia.

Location	Geographic coordinates	Mean temperature (°C)	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Precipitation (mm)
Kauai	21°88'79.43" N 159°49'23.15" W	24.4	29	24.4	939
Maui	20°47'57.07" N 156°02' 18.42" W	24.3	27.1	19.7	2051
New Caledonia	19-22°S 158-162°E	23.1	26	20.2	1530

Table VI.
Comparison of *Artocarpus camansi* (breadnut) production in McBryde Garden in Kauai, Hawaii, with the University of the West Indies Field Station in Valsayn, Trinidad and Tobago [27].

Years after being planted	Location	Average number of fruit	Average fruit weight (kg)	Average fruit length (cm)	Average fruit width (cm)	Number of seeds per fruit	Seed weight (g)	Seed mass per fruit (g)	Seed production per tree (kg)	Fruit production per tree (kg)	Seed mass / fruit mass (%)
5	UWI-FS	126	1.14	16.16	13.18	60	8.14	471.28	59.38	143.64	41.00
	McBryde Garden	19	1.51	16.50	15.00	44	11.41	502.00	9.54	28.61	33.33
6	UWI-FS	68	1.06	16.54	13.11	61	8.34	502.79	34.36	72.43	46.00
	McBryde Garden	36	1.92	17.77	16.77	53	8.42	443.33	15.92	69.10	23.03
7	UWI-FS	25	0.89	14.41	12.40	44	7.56	327.78	8.30	22.54	36.00
	McBryde Garden	52	1.61	18.27	15.37	49	8.73	428.26	22.23	83.68	26.56
8	UWI-FS	30	0.92	14.52	12.21	59	8.17	475.00	14.09	27.30	42.00
	McBryde Garden	23	1.33	18.66	14.55	31	9.18	284.46	6.63	31.06	21.34

UWI-FS: University of the West Indies Field Station.

breadfruit flowering is induced when the sun reaches its zenith before the summer months and subsequent fruiting extends throughout the summer months. Kauai and Maui share a similar longitude and latitude (*table V*); the similarity of the breadfruit seasonality in these datasets provides evidence in support of this hypothesis, but further studies in more widely different locations are required.

Figure 7.
Comparison of individual edible fruit seasonality profiles of breadfruit cultivars planted in the National Tropical Botanical Garden in Kauai and Maui, Hawaii. Edible/harvestable fruit refers to full-sized fruit, mature fruit and ripe fruit.

Figure 8.
Comparison of individual male flower seasonality profiles of breadfruit cultivars planted in the National Tropical Botanical Garden in Kauai and Maui, Hawaii.

On average, in our study, breadfruit trees produced some edible fruit each month every year. However, not all cultivars produced edible fruit at the same time and there were definite seasonal patterns (*figure 9*). Most trees bore edible fruit from March to May and from September to October. The fruit matured 3 to 4 months later than the male flowers, which is consistent with previous studies [15]. The most fruit was produced from July to November; about 70% of the trees in our study were in fruit for >80% of the years measured. Male flowers (>70%) reached a peak from July to December for >70% of the year in this study.

4. Conclusions

More than 80% of the world's undernourished people live in the tropical and subtropical regions, and food insecurity is increasing due to changing economics and climates. Developing breadfruit (*Artocarpus* spp.) as a sustainable agroforestry crop is a key component in feeding the hungry, increasing food security and boosting local economies. The current data describes breadfruit growth habits with a comparison of yield and seasonality, demonstrating the range of diversity among cultivars. Generally speaking, breadfruit, including hybrids, requires around 30 months to fruit from root cuttings. Once established, a breadfruit tree can produce over 250 fruits a year with an average weight of 1.2 kg. Around 60% of fruits are produced during the season from July to November. Our study demonstrated that the expected yield for breadfruit after 7 years is 5–8 t·ha^{-1}. Differences exist in cultivars. As expected, hybrids have many advantages, including yield, larger average fruits for mature trees, and denser tree canopies. Even though some cultivars (*A. altilis*: Toneno and White; *A. altilis* × *A. mariannensis*: Rotuma and Meinpadahk) have certain agricultural advantages, selecting cultivars for international distribution also depends upon the flavor, texture, taste, etc. of the cultivar. To date, Ma'afala is the first breadfruit cultivar available for widespread distribution. Tissue culture-propagated Ma'afala trees produced fruit within 23 months and these data indicate that an orchard of established Ma'afala trees will produce 8.5 t·ha^{-1} of fruits within 8 years. Seasonality for flower and fruit seasons remains similar between the two locations compared in this article, supporting the hypothesis that seasonality of breadfruit is closely related to the distance from the equator and incidence of light [15]. The data gathered in this article provide a practical forecast for breadfruit agricultural production. Further studies will determine whether the fundamental characteristics of breadfruit cultivars are conserved across disparate geographic regions and distant climates.

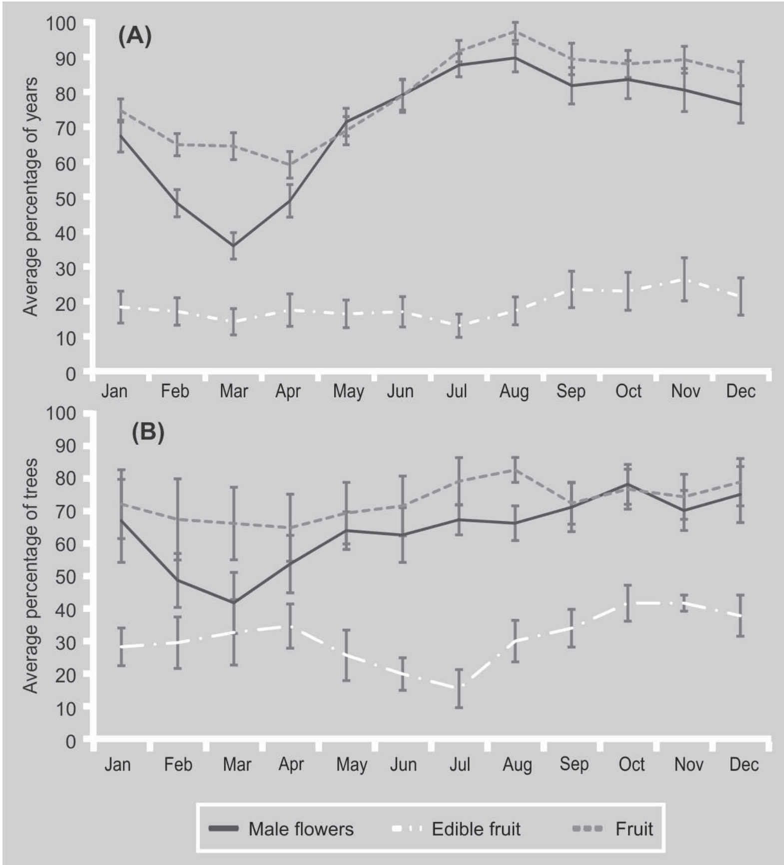

Figure 9.
(A) Average percentage of years that breadfruit trees bore fruit, edible fruit and male flowers from 2007 to 2012 in the National Tropical Botanical Garden in Kauai, Hawaii.
(B) Average percentage of breadfruit trees bearing fruit, edible fruit and male flowers from 2007 to 2012 at the NTBG in Kauai. Edible/harvestable fruit refers to full-sized fruit, mature fruit and ripe fruit. Bars represent the standard error of the mean.

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Productividad del cultivo, rendimiento y estacionalidad del árbol del pan (*Artocarpus* spp., Moraceae).

Resumen – **Introducción**. El árbol del pan, *Artocarpus* spp., es un cultivo de base, capaz de reducir el hambre y mejorar la seguridad alimentaria en las regiones tropicales. Actualmente, se necesitan directivas y recomendaciones enfocadas a la selección de variedades y a las técnicas de producción para implantar el árbol del pan en nuevas regiones. **Material y métodos**. Para responder a esta necesidad de extender el cultivo del árbol del pan, se estudió en 7 años, de 2002 a 2012, el crecimiento, el desarrollo, el rendimiento y la estacionalidad de 24 cultivares del árbol del pan (26 árboles) implantados en Kauai, Hawái. Se crearon perfiles de producción individual para cada cultivar, basándose en los principales parámetros de producción. **Resultados**. El conjunto de todos los cultivares del árbol del pan de la especie A. altilis produjo una media de 269 frutos por año y por árbol con un peso medio de los frutos de 1,2 kg. En base a una densidad de plantación de 50 árboles·ha^{-1}, esto se traduciría por un rendimiento medio previsible de 5,23 t·ha^{-1} después de 7 años. Los híbridos *A. altilis* × *A. mariannensis* tuvieron un rendimiento superior. Nuestros resultados sostienen la hipótesis propuesta anteriormente, la cual predecía la estacionalidad del árbol del pan. De media, el pico de producción tuvo lugar de julio a noviembre. **Conclusión**. El cultivar Ma'afala, primer cultivar comercial ampliamente disponible, comenzó a producir entre 22 y 23 meses después de su plantación. Los cultivares Toneno, White, Rotuma y Meinpadahk serían otros cultivares con un fuerte potencial para una producción comercial.

Hawaii / *Artocarpus* / frutas / fruta pan / ensayos de variedades / elección de especies / rendimiento de cultivos / estacionalidad / adaptación