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Frugivory and seed predation of fishtail palm (*Caryota mitis* Lour.) on the remote oceanic island of Narcondam, India

Short Communication

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Abstract

Oceanic islands, due to their evolutionary history and isolation, play a dual role of having high endemicity and being vulnerable to extinctions, with most known extinctions occurring on islands. Plant–animal interactions are particularly important on islands, as island systems generally have low redundancy and are more vulnerable to disruption either via extinction or by invasive species. Here, we examined the fruit removal and seed predation of a keystone palm, *Caryota mitis*, on Narcondam, a remote oceanic island. The island endemic Narcondam Hornbill (*Rhyticeros narcondami*) was the sole seed disperser of the palm (90 hours; $N = 15$ trees), with mean (± SE) visitation rate being 0.23 (± 0.06) individuals per hour and fruit removal rates of 3.5 (± 1.5; range: 0–16) fruits per visit, indicating a lack of redundancy in seed dispersal of the palm on this island. Whereas the invasive rodent, *Rattus* cf. *tiomanicus*, was the sole predator of palm seeds ($N = 15$ individual fruiting palms, 416 trap nights). Overall, 17.1% of the seeds placed ($N = 375$ seeds) were removed. Seeds placed under and away from the canopy, and at different densities (2 plots with 10 seeds each; 1 plot with 5 seeds, respectively), showed similar removal rates. This indicates density-independent seed predation and the lack of safe regeneration sites for *Caryota mitis*, with potential deleterious effects on subsequent stages of the 'seed dispersal cycle'. Here, from a data-deficient site, we provide baseline information on the plant–frugivore interaction of a keystone palm and the potential impacts of an invasive rodent.

1. Introduction

Due to their evolutionary history, isolation and size, islands are especially vulnerable to biodiversity loss (Moser *et al.* 2018). Globally, most known extinctions have occurred on islands (Bellard *et al.* 2016), making them crucial areas for conservation. Loss of endemic species and introduction of invasive species can have cascading impacts on key ecosystem processes, like seed dispersal and seed predation, especially on islands (Moser *et al.* 2018, Heinen *et al.* 2023). These key ecosystem processes ensure plant regeneration and maintenance of plant diversity in tropical forests (Wang & Smith 2002). Moreover, the initial stages of the seed dispersal cycle, namely, fruit removal and seed predation, determine the spatial template of the distribution of seeds in the forest (Wang & Smith 2002, Beckman & Rogers 2013). A disruption in these early stages of the dispersal cycle can have downstream consequences on the recruitment stage of the plants.

Islands have a smaller assemblage of frugivores compared to mainland, as such island endemic frugivores often play a pivotal role in seed dispersal. However, introduction of invasive rodents (in the absence of natural predators) can negatively impacts on plant regeneration via seed predation (Meyer & Butaud 2009, Traveset *et al.* 2009, Auld *et al.* 2010). Therefore, it is critical to determine the role of endemic frugivores in the seed dispersal process and the impacts of invasive rodents on the seeds of native plants, especially those that are vital for endemic frugivores.

Palms (Family: Arecaceae) are a quintessential component of tropical wet forests, whose seeds are generally dispersed by animals (Snow 1981, Couvreur & Baker 2013). They are known to be negatively impacted by invasive rodents on islands (Meyer & Butaud 2009, Auld *et al.* 2010) to the extent that rodents have been responsible for the local extinction of palms on certain islands like Hawai'i (Athens 2008) and Rapa Nui (Easter Island) (Hunt 2007). Notably, palms are an important fruit resource for frugivores on islands (Zona & Henderson 1989, Naniwadekar *et al.* 2021a). Many palm species provide copious amounts of fruits and have staggered fruiting, wherein the ripening of fruits on the palm is spread out over a wide temporal window, thereby providing frugivores ample fruit resources over a prolonged time period (Schaefer *et al.* 2002, Adler & Lambert 2008). This makes it interesting and important to determine seed dispersers of palms and the impacts of invasive rodents on palm seeds on oceanic islands.

In this study, we focus on the *Caryota mitis* Lour., a sympodial species of fishtail palm, to determine patterns of frugivory and seed predation on a remote oceanic island, Narcondam (area: 6.8 km^2; elevation range: 0–710 m ASL; 13.4456°N, 94.2633°E) in the Andaman sea in south Asia. Insights from previous studies show that *Caryota mitis* is consumed by over 14 vertebrate species, both birds and mammals (Quek *et al.* 2020). It is widely distributed and abundant in south-east Asian tropical forests. It is hapaxanthic, wherein, post an initial vegetative phase, all its resources are exhausted in a prolonged flowering phase (Uhl & Dransfield 1987). They produce substantial infructescence, up to 805 fruits per infructescence (Quek *et al.* 2020), in a basipetal sequence, thereby providing a continuous resource to frugivores and seed predators (Quek *et al.* 2020).

On Narcondam Island, *Caryota mitis* is one of the most abundant plant species of more than 210 flowering plant species recorded from the island (Table S1; Page *et al.* 2020). Like other palms, due to its staggered fruiting, *Caryota mitis* is likely to be an important resource for frugivores and seed predators on the island. This palm was found to be one of the most important large-seeded fruits in the diet of the island endemic Narcondam Hornbill (Naniwadekar *et al.* 2021a). The island is a relatively young volcanic island (~700,000 years old; Bandopadhyay 2017) and is unique due to the absence of small-bodied frugivores like bulbuls (Pycnonotidae), barbets (Megalaimidae) and Asian Fairy Bluebird *Irena puella*. These are important seed dispersers in mainland Asia. The island, however, has relatively larger-bodied avian frugivores, including the island endemic Narcondam Hornbill (*Rhyticeros narcondami*), two species of Imperial pigeons, *Ducula bicolor* and *Ducula aenea*, Asian Koel *Eudynamys scolopacea*, and Common Hill Myna *Gracula religiosa* (Naniwadekar *et al.* 2021a). Frugivorous bats have also been reported from the island, which may play an important role in the long-distance dispersal of plant species (McConkey & Drake 2015). Unlike some other Pacific Ocean islands (see Carpenter *et al.* 2020), there are no known extinctions of seed predators or dispersers from Narcondam Island. Given the importance of this palm for the island endemic hornbill, it is important to evaluate the potential impact of invasive rodents on these palms.

The Narcondam Hornbill is endemic to the small island of Narcondam and occurs in very high densities (~151 birds per km^2; Naniwadekar *et al.* 2021a). It is a central frugivore in the plant–frugivore community on the island (Naniwadekar *et al.* 2021a). Additionally, the oceanic island has a high abundance of rodents *Rattus* cf. *tiomanicus* (Ramachandran *et al.* unpublished data), which are likely to have been inadvertently introduced by humans. There have been a few previous expeditions to the islands which have reported a high abundance of invasive rodents; however, their ecological role has not been examined in detail (Vivek & Vijayan 2003, Shankar Raman *et al.* 2013). This provided an interesting set-up to examine the role of plant–animal interactions and any potential impacts by invasive rodents.

Here, using *Caryota mitis* as a focal taxon, we aimed to identify and determine the relative importance of different frugivores in its seed dispersal by conducting focal tree watches and to determine the impact of the invasive rodent on the seed predation of the palm via an experimental framework wherein seeds were laid at different densities (high and low) and at different distances from the fruiting individuals (under the canopy and away from the canopy). We expected that we would not find Janzen–Connell (Janzen 1970, Connell 1971) effects due to the high abundance of invasive rodents on the island, resulting in density-independent seed predation and a lack of safe sites for plant regeneration.

2. Methods

This study was conducted from December 2019 to February 2020. To examine the frugivory and seed predation of *Caryota mitis*, we employed two methods, focal tree watches to determine fruit removal rates by different frugivore species and seed plots to examine the seed fates. To determine the main seed dispersers of *Caryota mitis*, we observed 15 fruiting *Caryota mitis* individuals from 0600 hours to 1200 hours for five days. During the fruit tree watches, we recorded the frugivore species identity and the number of frugivores that visited the fruiting *Caryota mitis*. We also counted the number of fruits swallowed, pecked and dropped by the frugivores to estimate the fruit removal rate per visit. Additionally, we carried out night tree watches on five individual palms for 150 min over three nights to determine if any of the frugivorous bat species on the island dispersed the seeds of *Caryota mitis*.

To estimate the seed removal rates by the invasive *Rattus* cf. *tiomanicus* and other animals, we set up four seed plots (1 m × 1 m), under each of the 15 fruiting *Caryota mitis* palms. We selected trees with relatively high fruit crop sizes and ensured the minimum distance between the selected palms was greater than 30 m. Two plots, one exclosure plot and one seed plot were established below the focal fruiting palm, and two plots were laid 15 m away in opposite directions of the focal palm. The two plots below the focal palm (Exclosure and Below: high density) had 10 seeds each. In the two away plots, one had 10 seeds (Away: high density) and the other plot had five seeds (Away: low density). This was done to examine if the seed predators were influenced by either the density or distance from the focal tree. All the leaf litter was removed from within the plots. Under the canopy of *Caryota mitis*, there were generally a high number of seeds and fruits in the order of fifty to hundred among the focal trees. We followed established methods (Sidhu & Datta 2015, Gopal *et al.* 2021) and only retained marked and tagged seeds within the plot and removed any extra seeds. However, we did not alter the number of fallen seeds outside the plot. The number of seeds in away-high-density plots was decided based on earlier studies (Sidhu and Datta 2015, Krishnan *et al.* 2022) and due to logistical constraints. For low-density plots, we have used the number of seeds that are scatter-dispersed by hornbills in tropical forests as estimated at other sites in north-east India (Naniwadekar *et al.* 2021b). Unlike clump dispersal where seeds occur in high densities, scatter dispersal represents a low-density scenario. A free 50-cm Dacron fishing line was attached to the seed surface of each seed with a non-toxic super glue (Loctite® Super Glue Ultra Gel™) to track seed fate following Gopal *et al.* (2021) and Sidhu and Datta (2015) to ease detectability of marked seeds that are moved or predated upon. The seed plots were monitored weekly, and three seed fates, intact (seeds with no visible signs of predation), predated (seeds with bite marks or with remains) and removed (seeds missing from within 10 m radius of the plot), were recorded following Gopal *et al.* (2021). Whenever seeds were missing from the plot, two observers (AG and SG) looked for the seeds within a radius of 10 m surrounding the plot.

For further analysis, we merged the seed fates ‘removed’ and ‘predated’. Please see Table S3 for details of all the seed fates. The plots were monitored till all the seeds were removed or until the end of the study period. The seeds were monitored for a maximum period of 33 days (mean = 15.9 days, range = 6 – 33 days) from the day of setting up the seed predation plots. Camera traps were placed under the canopy of each of the 15 fruiting *Caryota mitis* palms (the same individuals under which seed plots were established; Below: high-density plot) to determine visitor diversity and visitation rates. The total camera trap effort across the 15 individual fruiting palms was 416 nights (range: 25–33; Table S2). We used a generalised linear model with a binomial error structure to determine whether the proportion of seeds removed differed among the three categories (Below: high, Away: high and Away: low). Additionally, we opportunistically examined the seed predation of six other tree species fruiting during the study period (total $N = 16$; *Aphanamixis polystachya*, *Canarium euphyllum*, *Chionanthus sp.*, *Codiocarpus andamanicus*, *Endocomia macrocoma* and *Planchonella longipetiolata*). For these species, we laid out two seed plots, one under the canopy (Below: high density) and one away (15 m) from the canopy (Away: high-density) with 10 marked and tagged seeds in each plot. Please refer to Table S2 for additional details.

3. Results

We observed Narcondam Hornbill in 11 of the 15 focal palm watches, while Asian Koel and Green Imperial pigeons were observed only in one focal palm watch. The mean (± SE) visitation rate of Narcondam Hornbill on *Caryota mitis* was 0.23 (± 0.06) birds per hour. The Narcondam Hornbill was observed handling 49 fruits, of which 71.4% were swallowed, 18.4% were dropped and 10.2% were inspected. The mean (± SE; range) fruit removal rate per visit was 3.5 (± 1.5; 0–16) fruits per visit. This includes only those fruits that the birds swallowed. During the focal palm watches, there were no observations of any other frugivores handling the palm fruits, including the Asian Koel and Green Imperial pigeon that visited the focal palm trees. Additionally, we did not observe any frugivorous bats visiting *Caryota mitis* during the night tree watches.

In 416 trap nights, the invasive *Rattus* cf. *tiomanicus* was found to be the sole vertebrate seed predator of the selected tree species on the island. The mean (± SE) visitation rate of the rodents was 1.75 (± 0.26) visits per trap night.

Despite thorough searches within 10 m of the plot, we did not find any evidence of caching or secondary seed dispersal. Of the 77 seeds of *Caryota mitis* that were removed, we either found predated seeds with fishing lines or fishing lines without seeds ($N = 41$), or we were unable to find the fishing line at all ($N = 28$).

For *Caryota mitis*, all the seeds in the exclosure plots were intact during the study period. However, for the other treatments, overall, 17.1% (SE = 3.06; range = 0–1; $N = 375$ seeds) of the seeds were removed. Notably, the proportion of seeds removed was similar across treatments, suggesting density-independent predation (Table 1; Fig. 1). The other tree species had more than 50% of the seeds predated, and a very low overall removal rate of 8% was observed. More than 90% of the seeds of *Codiocarpus andamanicus* and more than 85% of *Planchonella longipetiolata* seeds were predated across treatments (Table S3). On the other hand, while more than 70% of the seeds of *Canarium euphyllum* were intact, 70% of the seeds of *Aphanamixis polystachya* were removed (Table S3). *Planchonella longipetiolata* was the only species for which we found evidence of invertebrate predation, with 13% of seeds (out of 100 seeds) being predated by invertebrate seed predators (5% and 8% in Below: high density and Away: high density, respectively). However, there was no difference in the proportion of seeds that were removed between the plots under and away from the canopy, as inferred from overlapping SEs (Fig. S1).

Table 1. Summary of the generalised linear model with binomial error structure examining the relationship between the proportion of seeds removed across the three categories. The three categories are under the focal plant (Below: high density, 10 seeds per plot), away from the focal plant with high seed densities (Away: high density, 10 seeds per plot) and away from the focal plant with low seed densities (Away: low density, 5 seeds per plot)

	Estimate	SE	*z*	*p*
Intercept (Away: high density)	−4.961	3.107	−1.597	0.11
Away: low density	−1.060	6.105	−0.174	0.862
Below: high density	−0.257	4.701	−0.055	0.956

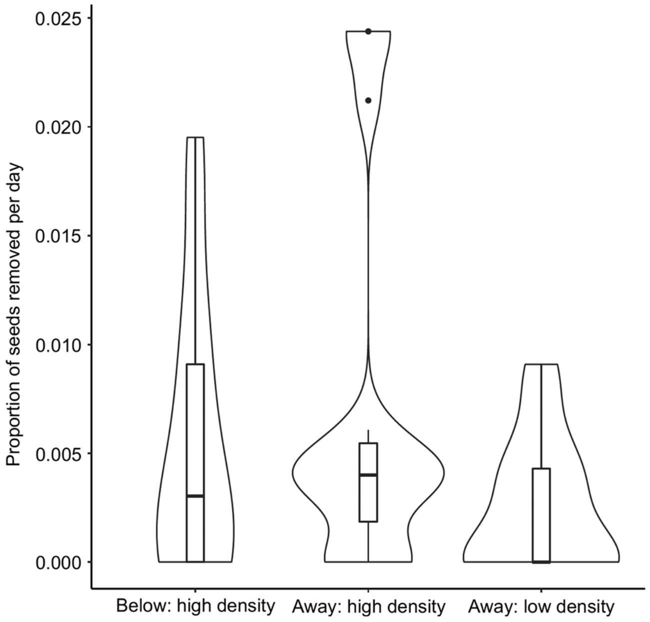

Figure 1. Violin plot (with box plots inside) depicting the proportion of seeds removed per day of *Caryota mitis* ($N = 15$) across the three categories, under the focal plant (Below: high density, 10 seeds per plot), away from the focal plant with high seed densities (Away: high density, 10 seeds per plot) and away from the focal plant with low seed densities (Away: low density, 5 seeds per plot).

4. Discussion

Here, from a data-deficient region of the Indian Ocean, we provide baseline information on the frugivory and seed predation of a keystone palm species. In terms of frugivory, unlike other sites (Quek *et al.* 2020), in 90 hours of observations, only the island endemic Narcondam Hornbill was seen dispersing the seeds of *Caryota mitis*. In terms of seed predation, the invasive rodents removed seeds in a pattern not consistent with the expectations of the Janzen–Connell hypothesis. Rodents removed seeds both near and away from the focal palms and in both low and high densities, indicating density-independent seed predation by the invasive rodents on the island. This is likely to reduce the safe sites for regeneration and can potentially alter the recruitment trajectory of the native flora over time.

Rattus cf. *tiomanicus*, although a species native to south-east Asia, is known to be invasive in certain parts of its native geographic range and is also very abundant in the secondary forests and oil palm plantations in south-east Asia (Chinkok *et al.* 2007, Gibson *et al.* 2013). The photo capture rates of *Rattus* on Narcondam Island were 2.9 times higher than a mainland site in southern India, where seed plots were laid out in fragmented forests under four different fruiting tree species (Gopal *et al.* 2021), indicating a higher predation pressure by rodents on the island. Future research needs to examine the impacts of rodent removal on palm regeneration on the island.

We also sampled opportunistically six other tree species, but unlike *Caryota mitis,* we could not find sufficient replicates for these. However, our preliminary data for these opportunistically sampled tree species also show similar seed removal rates near and away from the focal tree (Fig. S1; Table S3), indicating the pervasive impacts of the invasive rodents as seed predators. Unlike *Caryota mitis*, the seed removal rates were much higher for these species. The variation in seed removal rates across the different plant species points towards variable seed predation pressure, which could potentially alter the recruitment trajectory of plants on the island in the long term. All the tree species we studied are important food plants of the island endemic Narcondam Hornbill (Naniwadekar *et al.* 2021a). Further intensive sampling is warranted to determine if the predation of seeds by the invasive rodent has cascading downstream effects on the plant community in Narcondam Island.

Interestingly, we only found Narcondam Hornbill feeding on the fruits of *Caryota mitis*. Frugivorous bats can also potentially disperse the seeds of *Caryota mitis*; however, we did not observe them feeding on the palm fruits during our night tree watches. Imperial pigeons have been reported to disperse the palm seeds elsewhere (Quek *et al.* 2020), yet during our two-month stay on the island, we only found Imperial pigeons feeding on small-seeded plants (Naniwadekar *et al.* 2021a). Among the large-seeded plants on the island, *Caryota mitis* had high species strength values highlighting its importance for the hornbill (Naniwadekar *et al.* 2021a). Due to its relative abundance and its long, staggered fruiting period, *Caryota mitis* is an important food resource for the hornbill (Naniwadekar *et al.* 2021a).

There have been several previous expeditions to Narcondam that focused on the ecology of the island endemic hornbill. Although some do anecdotally report high densities of rodents (Vivek & Vijayan 2003, Shankar Raman *et al.* 2013), there have been no systematic efforts to estimate the densities of rodents and document their impact on the island biota. Although a before–after control–impact framework would have been ideal to conclusively examine the effects of the rodents, given the remoteness and ruggedness of the island, such information is lacking. Here, we provide some baseline information on the potential impact of the invasive rodents on the islands. One limitation of the study is that we did not enumerate the density of seeds below the focal plant. However, based on our observations, we are confident that the number of seeds were much higher below the tree than away from the tree. Moreover, given the absence of density-dependent effects documented in the study, this is unlikely to affect the outcome of the study. Invasive rodents have been shown to have deleterious impacts on other island biotas such as invertebrates, birds and crustaceans (Harper & Bunbury 2015). More intensive work is needed to systematically document the effect of these rodents on the Narcondam Island biota. Robust baseline data will help to identify the need for a management plan, in collaboration with the Forest Department and researchers, to control the invasive rodent populations on the island using established methods and by systematically documenting the effects of rodent removal on vegetation recovery as has been done elsewhere (Miller-ter Kuile *et al.* 2021).

Invasive species have caused catastrophic declines and extinctions of several native and endemic species, especially on islands. Due to their isolation, small size and unique evolutionary history, island systems are more susceptible to such invasions. Narcondam Island, by virtue of its small size, remoteness and lack of terrestrial mammals, exemplifies these threats. Further studies are required to understand the population density and dynamics of *Rattus* cf. *tiomanicus* and to resolve the biogeography and colonisation history of this species on the island. Systematic documentation and baseline information is needed on the densities of rodents and other key biotas on Narcondam Island to critically examine the impacts of the invasive rodent on the island biota and ecosystem of this unique island system.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0266467424000038

Data availability statement. Data is archived in the Dryad Digital Data repository; https://doi.org/10.5061/dryad.4tmpg4fjj.

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