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Original Article

Regeneration and self-thinning processes in a restored *Rhizophora apiculata* plantation in southern Thailand

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ABSTRACT

Degraded mangrove sites, such as abandoned shrimp ponds, are usually restored through the establishment of even-aged *Rhizophora apiculata* stands with an initial spacing of 1.5 m × 1.5 m. It has been observed that under good site conditions, densely planted *R. apiculata* trees compete from an early age onward. However, it is unknown whether early competition and self-thinning occur in recently restored mangrove plantations. The study was conducted in a 16-year-old *R. apiculata* stand established on an abandoned shrimp pond in Nakhon Si Thammarat province, southern Thailand. All trees were stem-mapped and their basal area was determined. Point process modeling was used to simulate the impact of self-thinning and regeneration processes on the spatial distribution of trees. Spatial statistics were applied to assess the goodness-of-fit of the simulated tree distribution compared to the observed distribution. Tree density declined from initially 4444 trees/ha to 3566 trees/ha, while the distribution of tree stems became more regular. The simulations indicated that 50% of all planted *R. apiculata* trees died due to self-thinning and 38% of all mapped trees regenerated naturally in close proximity to their mother tree. Moreover, planted trees tended to have a smaller basal area. The results suggest that the density of planted *R. apiculata* seedlings could be lowered in order to reduce the costs of mangrove restoration, as a large number of seedlings is lost due to density-dependent mortality.

Introduction

Mangrove forests grow along tropical and sub-tropical coastal regions and tolerate saline and anaerobic soil conditions (Tomlinson, 1994). These coastal wetlands are among the most productive and carbon-rich forests worldwide and provide numerous environmental services (Saenger, 2002). Mangrove forests protect the coastlines against soil erosion as well as storms (Mazda et al., 2002) and maintain water quality (Bayen, 2012). In Thailand, the area of mangrove forests has declined steadily from around 312,700 ha in 1975 (Department of Marine and Coastal Resources, 2010) to approximately 245,500 ha in 2014 (Department of Marine and Coastal Resources, 2015) due to the conversion of forest to infrastructure, residential areas and aquaculture, which has accelerated coastal erosion.

Most shrimp farms are abandoned after operating for more than 5 yr because of a sharp decline in productivity caused by high toxicity, diseases and acidification (Sathirathai and Barbier, 2001). Since the 1990s, restoration projects have been established to counteract the decline of mangroves (Aksornkoae, 1996). Many projects aimed at restoring abandoned shrimp ponds by establishing even-aged mangrove plantations consisting of only a single tree species which resulted in a uniform stand structure.

As forest stand development progresses after planting, trees begin to interfere with neighboring trees by competing for limited resources such as light, nutrients and fresh water (Silvertown and Charlesworth, 2009). Competition for light intensifies as forest gaps are filled by extending tree crowns following canopy closure. Growing competition among neighboring trees initiates size differentiation (Benjamin and Hardwick, 1986) and self-thinning processes, that is a decrease in forest density as tree size increases (Westoby, 1984). Seedlings were planted at a density of 1.5 m × 1.5 m or 4444 seedlings/ha in most of Thailand's mangrove restoration projects. If a majority of these planted seedlings died due to self-thinning at an early age, the costs of restoration could be reduced by lowering the initial seedling density. Although tree competition in young, even-aged plantations has been studied extensively in terrestrial forests, studies of these ecological processes in young mangrove plantations remain limited (Berger and Hildenbrandt, 2000; Berger et al., 2006).

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The current study was conducted in a 16-year-old *R. apiculata* plantation established on an abandoned shrimp pond. This mangrove tree species is found in the intermediate estuarine zone and tolerates a maximum salinity of 65 parts per trillion (Duke, 1992). *R. apiculata* is the most commonly planted and commercially used mangrove species in the Asia-Pacific region due to its fast growth and high caloric value, which makes it very suitable for charcoal production (Saenger, 2002; Duke and Allen, 2006). Due to the popularity of *R. apiculata* as a commercial mangrove species, its seedlings are widely available for use in restoration activities.

The objective of this study was to investigate the influence of tree-tree interaction on the spatial distribution of tree stems and their size in a *R. apiculata* plantation. The study aimed specifically at determining the mortality rate among planted seedlings, the percentage of trees that regenerated naturally among planted trees, and the intensity of tree competition. In general, the survival of seedlings and the subsequent forest development is rarely monitored after planting activities have been completed. Thus, spatial point pattern analysis was used in this study to infer ecological processes, such as tree-tree competition, from the mapped spatial distribution of tree stems (Perry and Enright, 2006; Law et al., 2009; McIntire and Fajardo, 2009).

Material and methods

Study site

The study was conducted in a mangrove plantation established as part of a species trial at Khanom in Nakhon Si Thammarat province on the coastline of the western Gulf of Thailand (Fig. 1). The average annual rainfall is 2496 mm and monthly values range from 68.0 mm in February to 631.2 mm in November (Thai Meteorological Department, 2013). The restoration of the site was initiated after the abandonment of these ponds due to water pollution and disease outbreak. Weeding of the herbs *Portulacastrum arundium* and *Acanthus ilifolius* was not necessary before planting, but the area was fenced to prevent encroachment and vandalism. Mature propagules were collected in nearby forests during the fruiting season and reared in polythene bags at local nurseries for 3–4 yr. Between March and May 1995, 3555 *R. apiculata* seedlings were planted on an area of 0.8 ha with a spacing of 1.5 m × 1.5 m (4444 trees/ha). One year after planting, the survival rate was very high (96%) considering the highly compacted soil surface, high soil temperature and high salinity in the abandoned shrimp pond (Japan Association for Mangroves, 1997). However, monitoring of seedling mortality was not conducted after the first year.

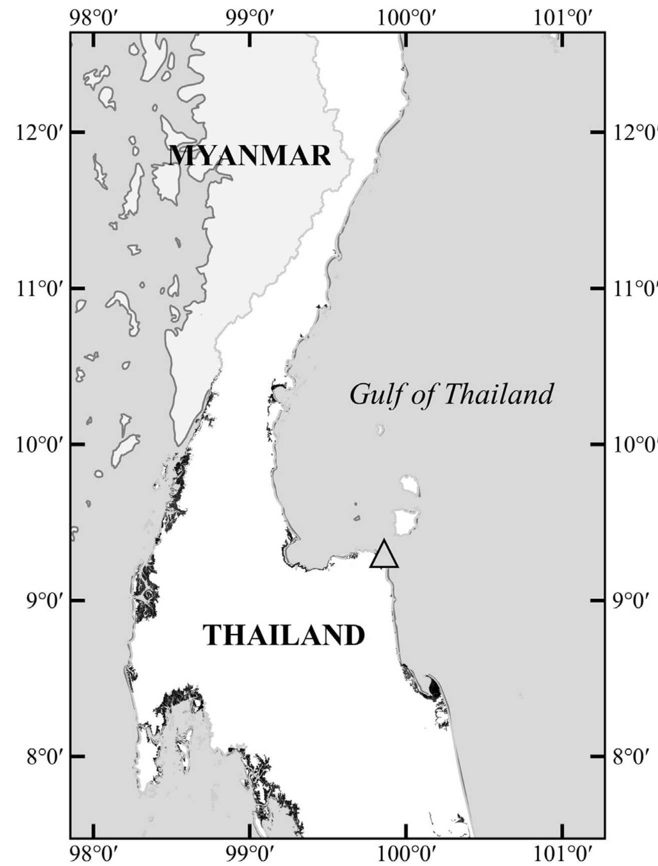

Fig. 1. Study site location (△) at Khanom in Nakhon Si Thammarat province, southern Thailand, where mangrove forests along Thailand's coastline are highlighted in black and the map was created using the global mangrove dataset from Giri et al. (2011).

Data collection

Mapping of the stem position of all trees (height ≥ 1.3 m) and seedlings (height < 1.3 m) within the restoration plot was undertaken in August 2011. In addition, the girth of each stem was measured at 20 cm above the highest prop root and the number of stems was recorded at the same height. The basal area of multi-stemmed trees was calculated by summing the basal area of each individual stem.

Data analysis

The pair-correlation function $g(r)$ was used to analyze the distance-dependent correlation of tree stems which describes the density of trees at a given radius r from a focal tree (Wiegand and Moloney, 2004; Getzin et al., 2008). The bivariate pair-correlation function $g_{\text{seedling-tree}}(r)$ describes the density of seedlings at a given radius r from a tree (Wiegand and Moloney, 2004). In addition, two distance distribution functions were used to further analyze the horizontal distribution of trees. First, the nearest-neighbor-distance distribution function $G(r)$ was applied, which shows the probability of a focal tree having its nearest neighboring tree within a distance r to determine the spacing between neighboring trees (Illian et al., 2008). Then, the empty space function $F(r)$ was used, which describes the cumulative distribution of distances between fixed locations and the nearest tree stem to evaluate the size of forest gaps (Illian et al., 2008).

Inference based on spatial point pattern analysis requires appropriate hypotheses which link each ecological process to a spatial point pattern (Wiegand and Moloney, 2004; McIntire and Fajardo, 2009). A systematic point pattern process was simulated to recreate the initial distribution pattern of planted trees with 1.5 m × 1.5 m spacing. Subsequently, a random thinning procedure was applied to recreate the effect of self-thinning processes on the spatial pattern of planted trees. Lastly, the natural regeneration of *R. apiculata* was simulated by superimposing a set of randomly placed points. The number of these randomly placed points was the difference between the observed number of trees and the number of points which remained after the thinning procedure. Thus, the final number of simulated points was equal to the number of observed trees. The simulated point pattern was fitted to the observed spatial pattern of trees through stepwise changes of the thinning intensity. The deviation of the observed tree distribution from the simulated pattern at a distance r was assessed based on simulation envelopes of $g(r)$, $F(r)$ and $G(r)$ which were constructed by repeating each point process simulation 199 times. The boundaries of each envelope were formed by the fifth-highest and the fifth-lowest values providing a significance level of $\alpha = 0.05$ (Baddeley et al., 2014).

Point patterns not only describe the location of points but can also contain more detailed information about certain attributes among points (Illian et al., 2008). Additional attributes which are attached to points are referred to as *marks*. The mark correlation function $\kappa_{mm}(r)$ was applied to analyze the spatial size-correlation of the tree basal area and number of stems based on the distance r between the stem position of two trees (Stoyan and Penttinen, 2000). Specifically, $\kappa_{mm}(r)$ shows whether trees which are separated by the distance r are of average size, above or below average size (Illian et al., 2008). Deviations of the mark-correlation function were tested based on independent marking (Illian et al., 2008). Hence, envelopes were constructed by fixing the point locations of trees and randomly re-assigning quantitative marks to each point in order to remove any spatial associations of the marks (Baddeley, 2010). Envelopes were constructed based on the fifth-highest and the fifth-lowest values of 199 simulations as well.

The R package spatstat (version 1.40–0) was employed for conducting all point pattern analyses (Baddeley and Turner, 2005). All figures were created with the ggplot2 package (version 2.0.0, Wickham, 2009).

Results and discussion

The mapped plot (0.49 ha) in the 16-year-old stand of *R. apiculata* had a mean tree density of 3566 trees/ha, which was approximately 80% lower than the initial planting density (4444 trees/ha). Trees had on average a basal area of 45.84 cm^2; the basal area of 97.2% of trees was smaller than 100 cm^2. The distribution of basal area was uni-modal and right-skewed—typical for young, even-aged forest stands (Fig. 2A). The majority of trees (62.4%) had multiple stems (Fig. 2B).

The pair-correlation function $g(r)$ of trees (Fig. 3B) clearly showed that systematic planting has resulted in a regular pattern with local maxima in distance-correlation at 1.5 m, 2.1 m and 3 m, that is the distance to the nearest, second-nearest and third-nearest neighbor. However, the hard-core process at $r < 1.5$ m in the simulated systematic pattern did not appear in the observed pattern, which was also more randomly distributed ($g(r) = 1$). Both departures of the observed from the systematic planting pattern revealed the presence of self-thinning and natural regeneration.

The nearest-neighbor function $G(r)$ shown in Fig. 3C indicated that more than 56.4% of all trees had a nearest neighboring tree within a distance of less than 1.5 m and only 5% of all trees were separated more than 1.5 m from their nearest neighbor. Only for the remaining 38.6% did the nearest neighbor distance match the minimum planting distance (1.5 m). Furthermore, the empty-space function $F(r)$ shown in Fig. 3C revealed that the maximum distance between any location in the plot to the nearest tree stem was 2.3 m, indicating that the maximum size of forest gaps increased 2.2 times compared to the initial planting pattern (1.1 m, Fig. 3D).

The concurrent influence of regeneration and self-thinning processes prohibited a direct estimation of the mortality of planted trees and the number of self-regenerated trees based solely on the change in forest density. Considering Fig. 3B–D, a thinning intensity of approximately 50% resulted in the best model fit suggesting that 50% of the initially planted trees died and that 38% of trees in the mapped forest stand regenerated naturally. This density reduction indicated the presence of self-thinning processes due to intensive competition among crowded trees as observed by Khoon and Eong (1995) in *R. apiculata*-plantations in Matang, Malaysia. Considering the high rates of seedling survival (96% in the first year, according to Japan Association for Mangroves, (1997)), it is suggested that the initially harsh environmental conditions were not the likely cause of the observed decline in tree density.

In addition to tree stems, the position of *R. apiculata* seedlings was mapped, having a mean density of 2723 seedlings/ha. The bivariate pair-correlation function $g_{seedling\text{-}tree}(r)$ shown in Fig. 3A indicated that the establishment of *R. apiculata* seedlings around trees was significantly inhibited in the immediate vicinity of trees ($r < 0.5$ m), but slightly aggregated between 0.5 and 1 m distance to tree stems and randomly distributed at $r > 1$ m. Therefore, the majority of *R. apiculata* propagules were dispersed only by gravitation and rooted before they could have been displaced by the outgoing tide.

The mark-correlation function (Fig. 4) was applied to two tree attributes—basal area and number of stems—based on the stem position of each tree. The mark-correlation function $\kappa_{mm}(r)$ revealed that basal area was negatively correlated most strongly at $r = 1.5$ m, that is at the initial planting distance. Thus, neighboring trees at a distance of 1.5 m had smaller stems than the average tree suggesting that younger, naturally regenerated trees are more likely to be multi-stemmed compared to planted trees. In contrast, the number of stems was not significantly dependent on the proximity of other trees at $r = 1.5$ m. Thus, the stem number was not reduced by competitive pressure from neighboring trees.

The findings suggest that the strongest competition occurred among planted trees which were established at a distance of 1.5 m.

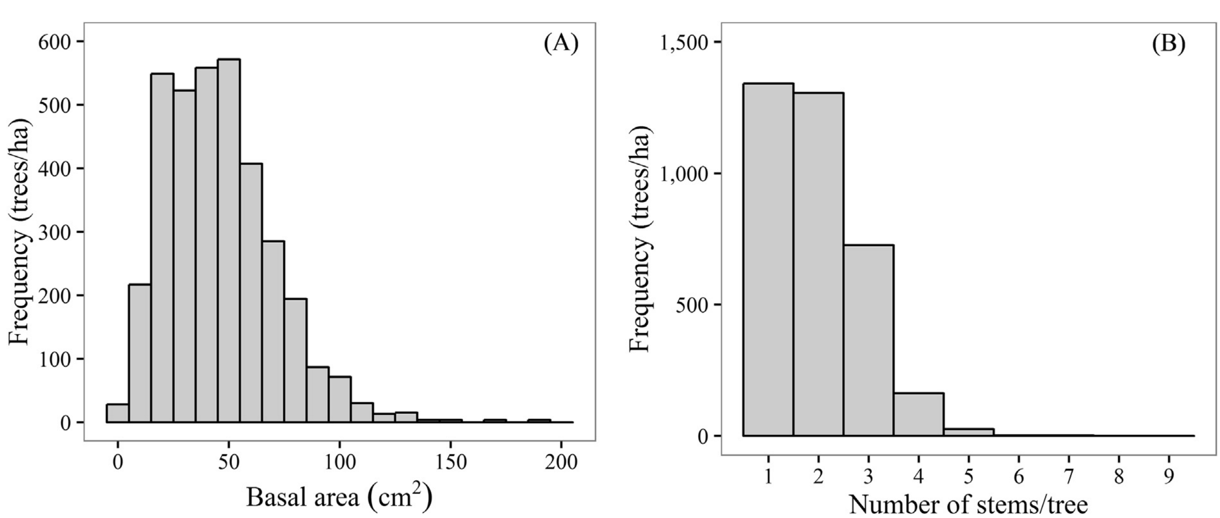

Fig. 2. Histogram of: (A) tree basal area; (B) number of stems per tree.

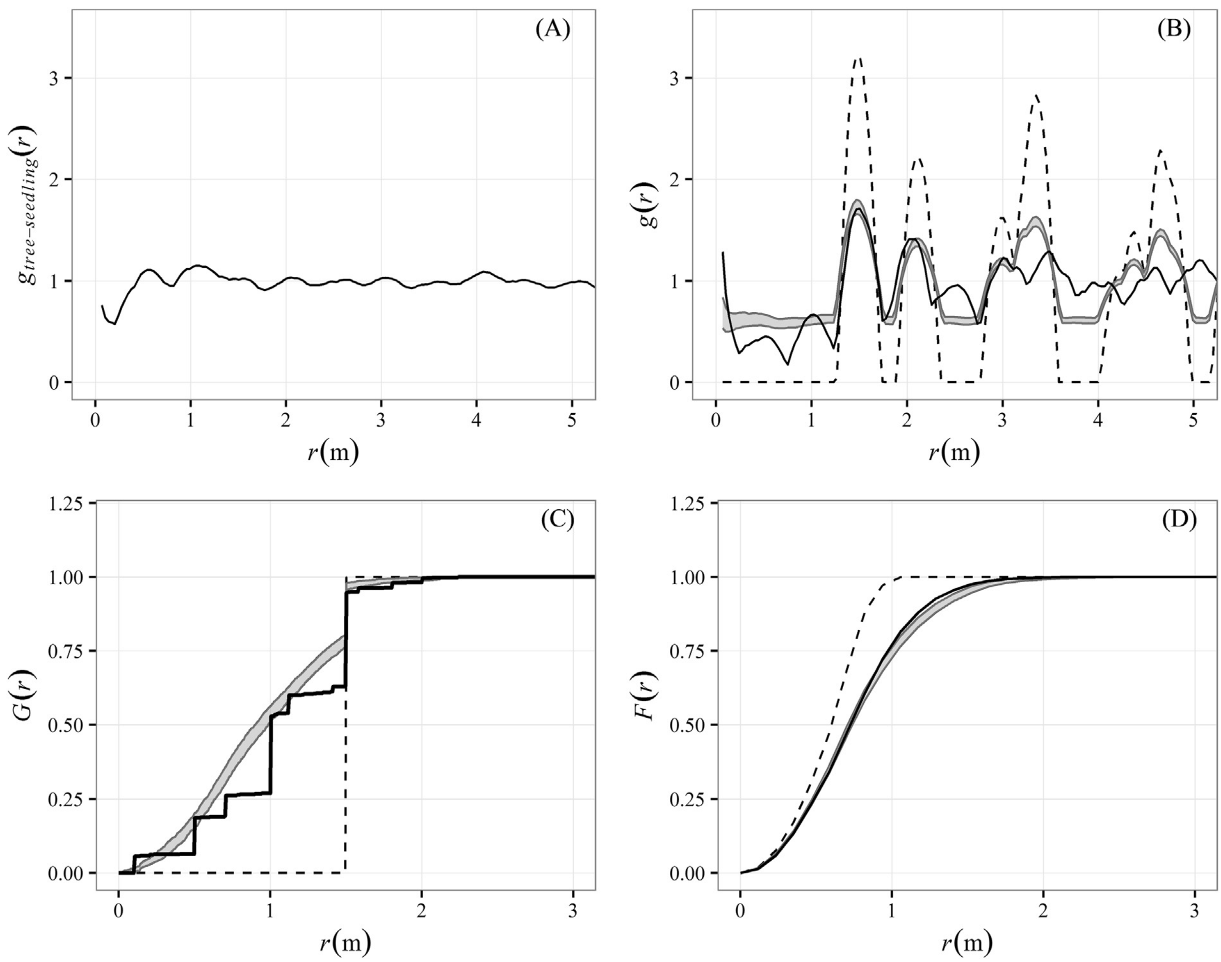

Fig. 3. Point pattern analysis of *R. apiculata* stand: (A) bivariate pair-correlation of trees to seedlings $g_{\text{seedling-tree}}(r)$; (B) univariate pair-correlation function $g(r)$ of trees based on stem coordinates, where values above $g(r) = 1$ indicate clustering, whereas values below would indicate regularity; nearest neighbor distribution function $G(r)$ indicates the probability of a tree having its nearest neighboring tree at distance r; (C) empty space function $F(r)$ indicates the average size of forest gaps; (D) solid lines indicate the observed seedling pattern (A) or observed tree pattern (B–D) based on radius r from the stem position; dashed lines represents the planting pattern with a spacing of 1.5 m × 1.5 m (4444 trees/ha); the gray envelope is based on the random removal of 50% of these systematically placed points superimposed by randomly placed points (1344/ha).

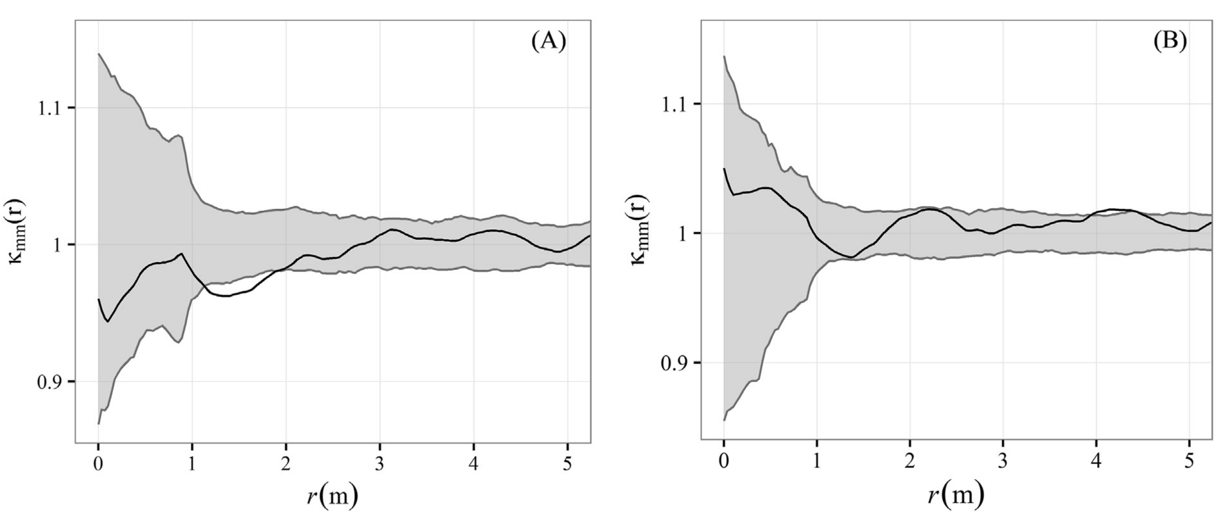

Fig. 4. (A) Mark-correlation function $\kappa_{mm}(r)$ for tree basal area; (B) number of tree stems/tree, based on radius r from the stem position of a focal tree, where solid lines indicate the observed mark correlation; The gray-shaded area indicates mark independence and is bordered by upper and lower dark-gray simulation envelopes; values $\kappa_{mm}(r)$ above the simulation band at distance r indicate that tree attributes of neighboring trees are on average larger than the stand's mean value (positive mark-correlation), whereas values below the band indicate that tree attributes of neighboring trees are on average smaller than the stand's mean value (negative mark-correlation).

Khoon and Eong (1995) observed self-thinning in the highly-productive mangrove plantations of Matang (Malaysia) at a similar age and recommended conducting thinning operations 13 yr after planting to reduce timber waste. It could be argued that the initial spacing of 1.5 m × 1.5 m was unnecessarily dense because natural regeneration was high and tree competition strong in the studied forest stand. However, it is unknown whether the high survival rate of planted seedlings was a direct result of their dense spacing as suggested by Kumara et al. (2010).

In conclusion, spatial point pattern analysis was used to analyze the mortality and regeneration of *R. apiculata* trees in a young plantation stand established on an abandoned shrimp pond based on their stem position. The fitted model suggested that approximately 50% of all planted trees died due to competition-induced self-thinning and that 38% of the current stand regenerated naturally. Moreover, the results showed that competition among planted trees affected their size negatively. It is not feasible to observe the long-term development of natural and planted mangrove forests over centuries in order to understand mangrove forest dynamics. However, the current investigation showed that spatial statistics, specifically point pattern modeling, can be applied to infer the presence of regeneration and self-thinning processes using cross-sectional data collected at one point in time.

Conflict of interest

There is no conflict of interest.

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