



# Bombax ceiba is a Good Native Tree Species for Performing Reforestation to Restore Highly Degraded Tropical Forests in Hainan Island, China

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Reforestation is an effective way to alleviate deforestation and its negative impacts on ecosystem services. It is widely recognized that the most key step for reforestation is using suitable native species, but selecting suitable native tree species is much more complex and challenging than the selection of non-native tree species that have been widely used for reforestation. Here, we quantify whether the native tree species (*Bombax ceiba*) can be suitable for performing reforestation to restore a 0.2 km<sup>2</sup> highly degraded tropical monsoon forest in Baopoling Mountain (BPL), Sanya, China, due to 20 years of limestone mining for cement production. We found that stomatal closure helped *Bombax ceiba* develop higher drought stress tolerance than the most dominant native tree species (*Bridelia tomentosa*) in an undisturbed tropical rainforest in BPL, thereby better adapting well to drought stress in the dry season. These characteristics in turn facilitated it to have high survival rate (92% ± 4%) and fast growth rate, after three years of monoculture in BPL. Thus, *Bombax ceiba* is very suitable for performing reforestation to recover highly degraded tropical forests in Hainan Island, China.

**Keywords:** drought stress tolerance, fast-growing, functional trait, native species, non-native species, reforestation

## INTRODUCTION

Historic human disturbance (e.g., ore mining and agricultural use) has resulted in very high rates of deforestation and degradation worldwide, which has become a major threat to global biodiversity and ecosystem services (e.g., freshwater supply and slowing down of global warming) (Sahin and Hall, 1996; Foley et al., 2011; Lambin and Meyfroidt, 2011; Vörösmarty et al., 2015). Reforestation is assumed to be able to partly alleviate deforestation-induced consequences (Griscom et al., 2017; Taubert et al., 2018). Thus, a number of reforestation projects have been performed worldwide to alleviate these native influences (Postel and Thompson, 2005; Calder and Aylward, 2006; Grime, 2006; Calder, 2007; Jian et al., 2015). However, to date, monoculture plantations of many non-native fast-growing and commercial tree species are the main strategy for reforestation in many areas across the world (Lu et al., 2017).

Although these monoculture plantations of non-native species can quickly facilitate reforestation, they can also increase risks including high cost for maintaining soil water and its nutrients and pest and pathogen outbreaks, besides having few benefits for ecosystem services (Lamb et al., 2005;

Wingfield et al., 2015). Thus, many studies emphasize the most key step for reforestation is using suitable native species but not non-native species (Miyawaki, 2004; Hall et al., 2011). However, selecting suitable native tree species is much more complex and challenging than the selection of non-native tree species, in particular (Meli et al., 2014; Stanturf et al., 2014). That is because the reforestation project usually has to be finished in a very short time and with limited economic resources. Moreover, in theory, mono-planting fast-growing tree species with high survival rates may be very effective for preventing high risks of landslide due to frequent typhoon and heavy rain in humid tropics (Stokes et al., 2009; Walker et al., 2009; Pang et al., 2018). Thus, non-native tree species which have high survival and growth rates and germination traits enabling easy propagation in the nurseries are the first choice for performing reforestation (Meli et al., 2014). Although pioneer native tree species in the early successional tropical rainforest are assumed fast-growing (Lohbeck et al., 2013; Zhu et al., 2013), their survival and growth rates and germination traits are very less investigated and thus cannot promise they are better than the non-native tree species for quickly finishing the reforestation project. Tree species in late successional or natural tropical rainforests may better adapt well to a specific environment of the highly degraded ecosystem than the non-native tree species, but they are treated as slow-growing, but with high resources competitive ability (Mason et al., 2012; Mason et al., 2013). As a result, they are also not very suitable for performing reforestation in humid tropics.

The currently developed trait-based method can open a good avenue for facilitating selection of suitable native tree species (McGill et al., 2006; Laughlin, 2014). It assumes that plant functional traits can directly reflect plants adapting well to different abiotic and biotic environments (Larjavaara and Muller-Landau, 2010; Laughlin and Laughlin, 2013; Cadotte, 2017). Thus, using the functional traits to find out native species that can not only have high survival and growth rates and germination traits enabling quick and easy propagation in the nurseries but also adapt well to the specific environment of the highly degraded ecosystem can be useful for reforestation. This goal may be easily achieved by comparing the functional traits which are highly correlated with survival and growth rates, germination, and the ability of adapting well to the environment of the highly degraded ecosystem between potential native tree species and dominant native tree species in the late successional or undisturbed old tropical rainforest.

*Bombax ceiba* is a native species, which is widely distributed in tropics, and it is also a high-demand plant species used for sculpture, so its seedling has been widely cultivated to get economic profits (Griffiths et al., 2003). In addition, it can adapt well to a very severe environment (e.g., drought stress), and thus, it may have high potential to be utilized for reforestation in the degraded tropical forest which has seasonal drought stress. Here, we mono-planted *Bombax ceiba* to restore a 0.2 km<sup>2</sup> highly degraded tropical rainforest in Baopoling Mountain (BPL) in Sanya, Hainan Province,

China, to quantify whether *Bombax ceiba* can be a good native tree species for reforestation in Hainan Island. It has been found that BPL can have frequent typhoon and heavy rain and very limited precipitation in the dry season (Hong et al., 2020), which may result in a high risk of landslide and drought stress during reforestation. Based on this, we use the following standards to judge whether *Bombax ceiba* can be a good native tree species for reforestation in extremely degraded tropical rainforests. First, *Bombax ceiba* can have high growth and survival rates, thereby being suitable for quickly performing reforestation. Second, landslides can be prevented after mono-planting *Bombax ceiba* to perform reforestation. Third, *Bombax ceiba* can adapt better to the seasonal drought in BPL than the most dominant native species in the undisturbed old tropical rainforest. Specifically, we survey survival and growth rates during reforestation. We also compare differences in functional traits that are highly associated with growth (i.e., photosynthesis rate) and drought stress tolerance (e.g., leaf turgor loss point) between *Bombax ceiba* and the most dominant native tree species in the adjacent undisturbed old tropical rainforest in BPL.

## MATERIALS AND METHODS

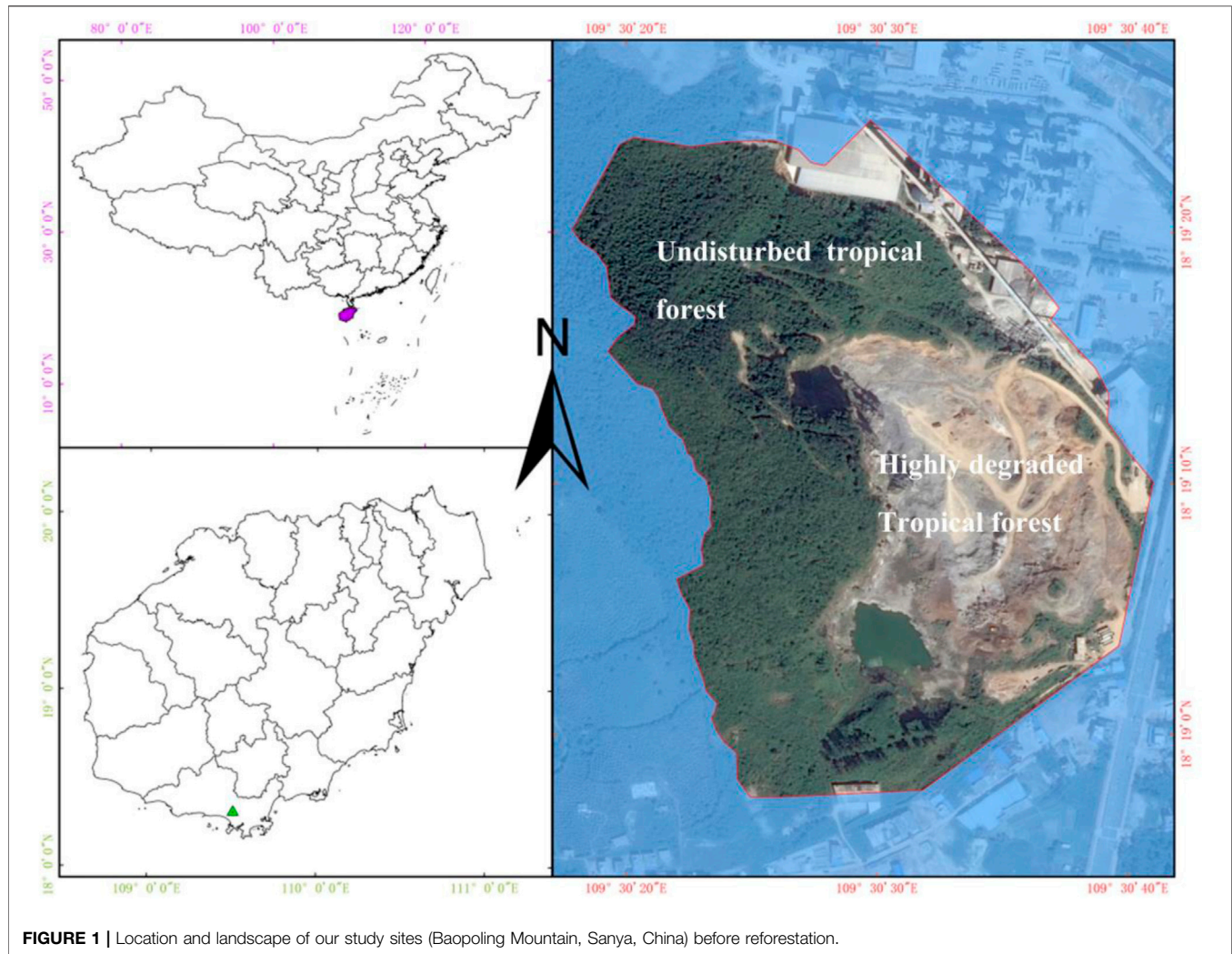
### Study Sites

Our study site is located in Baopoling Mountain (BPL) which is a limestone mountain in Sanya, Hainan Province, China (109°51'01"E, 18°31'99"N) (Figure 1). It has a tropical monsoon oceanic climate with the mean annual temperature of 28°C. The average annual precipitation in Sanya is 1500 mm, with approximately 91% of the precipitation occurring between June and October; these estimates are based on the climate data from 1959 to 2015 (Luo et al., 2018). The typical vegetation is the species-rich tropical rainforest (Luo et al., 2020), but *Bombax ceiba* is not the native tree species in this forest but the native tree species that is widely distributed in the whole Hainan Island, China. Due to 20 years of limestone mining for producing cement, one part (0.2 km<sup>2</sup> area) of BPL has become a highly degraded bare rocky mountain, where plants cannot be grown. Areas of BPL outside of this degraded area have not received any significant disturbance and remain as an undisturbed old tropical monsoon forest which has more than 120 tree species (Figure 1). In 2016, we have mono-planted the seedling of *Bombax ceiba* to perform a reforestation project in this 0.2 km<sup>2</sup> area. The planting density was kept at 80–100 stems per hectare; we recorded their survival rates from 2016 to 2019 as

$$\text{survival rate} = \frac{\text{remaining seedlings}}{\text{original seedlings}} \times 100\%.$$

### Trait Collection and Measurement

Since there is a remarkable dry season in BPL, plant species must develop high drought stress tolerance, thereby being able to survive well in BPL. Thus, in the peak of dry season (February) in 2019, we measured functional traits that are



**FIGURE 1** | Location and landscape of our study sites (Baopoling Mountain, Sanya, China) before reforestation.

**Table 1** | Mean DBH (in cm) of *Bombax ceiba* and *Bridelia tomentosa* in Baopoling Mountain and DBH values (in cm) of the sampled individuals (*n*) for *Bombax ceiba* and *Bridelia tomentosa*, respectively.

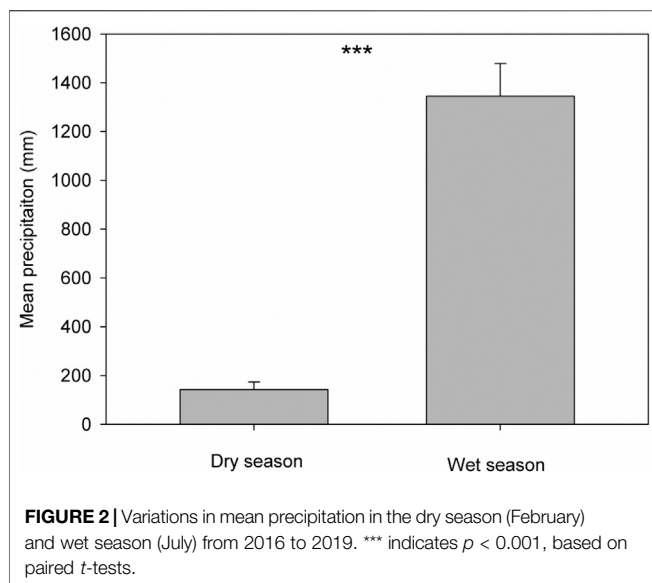
Species name	<i>n</i>	Mean DBH	DBH of sampled individuals				
			Tree 1	Tree 2	Tree 3	Tree 4	Tree 5
<i>Bombax ceiba</i>	5	11.2	12.1	11.5	10.8	10.2	10.5
<i>Bridelia tomentosa</i>	5	7.9	6.2	7.1	7.6	8.2	9.5

highly related to fast growth and drought stress tolerance (i.e., upper epidermis thickness ( $\mu\text{m}$ ), palisade tissue thickness ( $\mu\text{m}$ ), spongy tissue thickness ( $\mu\text{m}$ ), lower epidermis thickness ( $\mu\text{m}$ ), stomatal density (numbers  $\text{mm}^{-2}$ ), transpiration rate ( $\text{mol m}^{-2} \text{s}^{-1}$ ), maximum photosynthesis rate ( $\text{mol m}^{-2} \text{s}^{-1}$ ), stomatal conductance ( $\text{mmol m}^{-2} \text{s}^{-1}$ ), and leaf turgor loss point (MPa)) for *Bombax ceiba* and the most dominant (relative abundance >10%) plant species (*Bridelia tomentosa*) located in the nearby undisturbed forests. For measuring these traits, we first measured

the diameter at breast height (DBH) of all individuals for both *Bombax ceiba* and *Bridelia tomentosa* to get the mean DBH for *Bombax ceiba* and *Bridelia tomentosa*, respectively (see **Table 1**). Then, 20 fully expanded, healthy, and sun-exposed leaves were collected from five mature individuals of *Bombax ceiba* and *Bridelia tomentosa* whose DBH values were comparable to the mean DBH values of *Bombax ceiba* and *Bridelia tomentosa* (**Table 1**).

### Measurement of Leaf Anatomical Traits

Twenty mature and sun-exposed leaves were collected from five independent individuals of *Bombax ceiba* and *Bridelia tomentosa* in BPL. All leaf samples were progressively dehydrated in an ethanol series (50, 70, 85, 95, and 100%) and infiltrated with warm paraffin. Then, the thickness of the leaf, upper epidermis, lower epidermis, spongy tissue, and palisade was measured with a Leica DM2500 light microscope (Leica Microsystems GmbH, Wetzlar, Germany). The density of stomata was measured using a razor to slice the abaxial epidermis. All the sections were



mounted on slides and observed under a Leica DM2500 microscope.

## Measurement of Maximum Photosynthesis Rate, Transpiration Rate, and Stomatal Conductance

Measurements of the maximum photosynthesis rate, transpiration rate, and stomatal conductance were conducted between 9:00 and 11:00 on sunny days with an Li-6400 portable photosynthesis system (Li-Cor, Lincoln, Nebraska, United States). Based on preliminary trials, the photosynthetic photon flux density was set at  $1500 \mu\text{mol m}^{-2} \text{s}^{-1}$  to ensure that light-saturated photosynthetic rates were measured for *Bombax ceiba* and *Bridelia tomentosa*. Ambient  $\text{CO}_2$  and air temperature were maintained at  $390 \mu\text{mol mol}^{-1}$  and  $28^\circ\text{C}$ , respectively (Zhang et al., 2018a). Before data were recorded, leaves were exposed to the above conditions for about 5 min to allow photosynthetic parameters to stabilize.

## Measurement of Leaf Turgor Loss Point

Leaf-bearing branches from three to five individuals of each species were harvested and transported to the laboratory where the basal ends of the branches were immersed in distilled water and re-cut. The branch samples were rehydrated until the leaf water potential was greater than  $-0.05 \text{ MPa}$ . Leaves were first weighed to obtain the initial fresh mass and then immediately placed in a pressure chamber to determine the initial water potential. The leaf mass and water potential were measured periodically during slow desiccation in the laboratory. Finally, leaves were oven-dried for 72 h at  $70^\circ\text{C}$  to determine their dry mass. The leaf turgor loss point was determined using a pressure-volume relationship analysis program developed by Schulte and Hinckley (1985).

## Statistical Methods

First, we log-transformed all measured nine functional traits (upper and lower epidermis thickness, palisade and spongy tissue thickness, stomatal conductance, stomatal density, maximum photosynthesis rate, transpiration rate, and leaf turgor loss point) for *Bombax ceiba* and *Bridelia tomentosa* in BPL. Then, we used the paired  $t$ -test to quantify whether *Bombax ceiba* could have higher growth rates and drought stress tolerance than *Bridelia tomentosa*. Then, a principal component analysis (PCA) was employed to evaluate which of the 10 traits were best at discriminating between *Bombax ceiba* and *Bridelia tomentosa*.

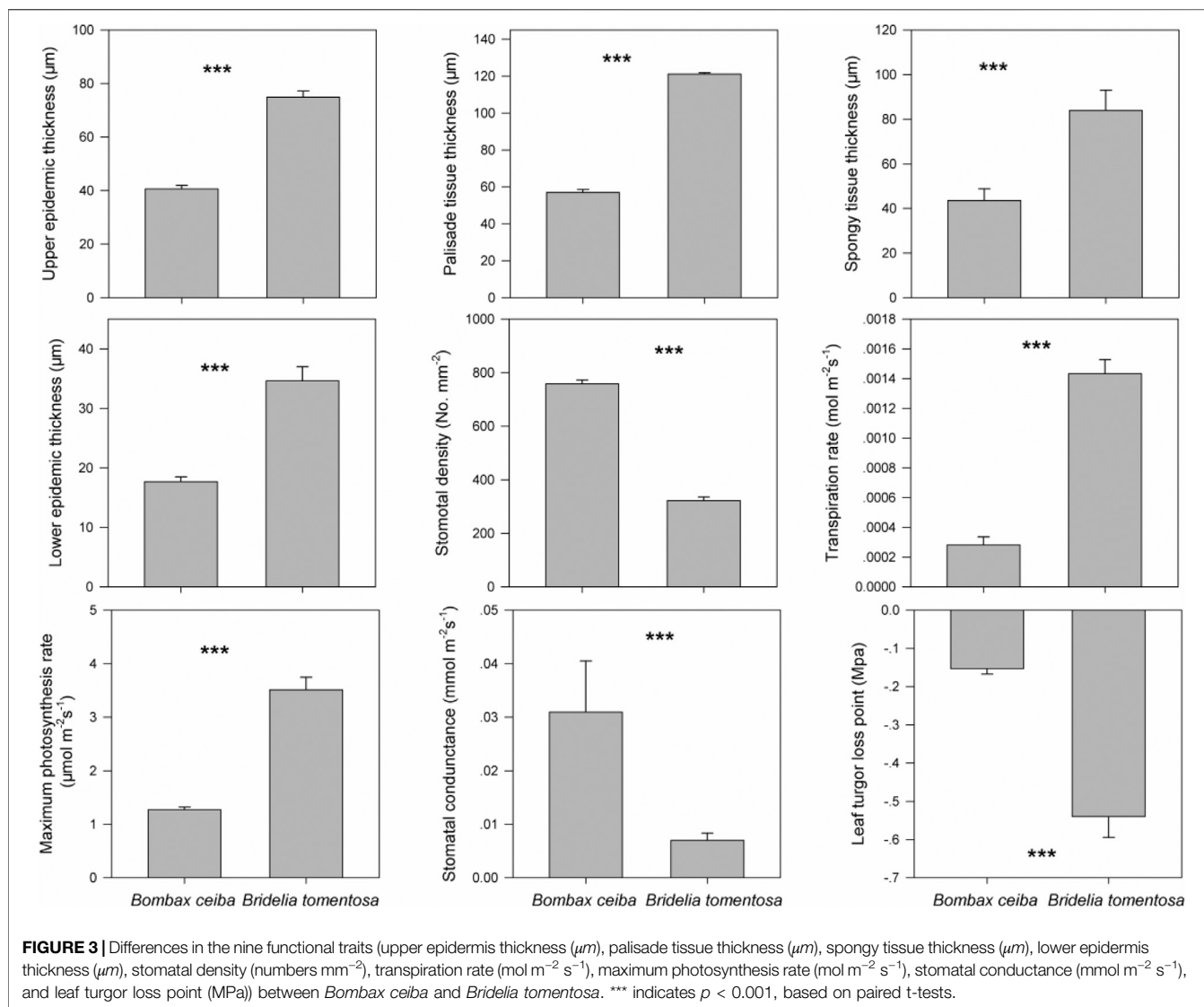
## RESULTS

Based on the precipitation records per month from 2016 to 2019, the mean precipitation in BPL in the dry season (February) was significantly much lower (only 1/10th) than that in the wet season (July) (Figure 2). However, after 2 years of plantation in BPL, the survival rate for all seedlings of *Bombax ceiba* was very high ( $92\% \pm 4\%$ ), and till now, we did not observe any destructive landslides (Figure 1). *Bombax ceiba* had a much higher growth rate than *Bridelia tomentosa*. That was because all seven traits (upper and lower epidermis thickness, palisade and spongy tissue thickness, stomatal conductance, maximum photosynthesis rate, and transpiration rate) that are highly associated with the growth of *Bombax ceiba* were all significantly much higher (3–5 times) than those of *Bridelia tomentosa* (Figure 3). In addition, *Bombax ceiba* had much higher drought stress tolerance than *Bridelia tomentosa*, as the leaf turgor loss point for *Bombax ceiba* was significantly much lower (merely 1/3rd) than that of *Bridelia tomentosa* (Figure 3). The results from the PCA indicated that only stomatal conductance was best at discriminating between *Bombax ceiba* and *Bridelia tomentosa* (Figure 4 and Table 2).

## DISCUSSION

Our results clearly revealed that when planting *Bombax ceiba* in Baopoling Mountain (BPL) for performing reforestation, we found that *Bombax ceiba* had a very high survival rate ( $92\% \pm 4\%$ ) and that mono-planting *Bombax ceiba* can indeed prevent landslides. Moreover, *Bombax ceiba* had a higher growth rate and drought stress tolerance than the most dominant native tree species (*Bridelia tomentosa*) in the nearby undisturbed tropical rainforest when facing the limited water supply in the dry season. Thus, *Bombax ceiba* can be suitable for performing reforestation to restore the highly degraded tropical forests in BPL.

We found that the photosynthetic rate for *Bombax ceiba* was much higher (3 times) than that of *Bridelia tomentosa*. The photosynthetic rate impacts the energy balance of a plant, where, typically, a high photosynthetic rate is linked to a fast-growing rate (Kirschbaum, 2011; Zhang et al., 2018b). This indicated that *Bombax ceiba* could have a higher growth rate

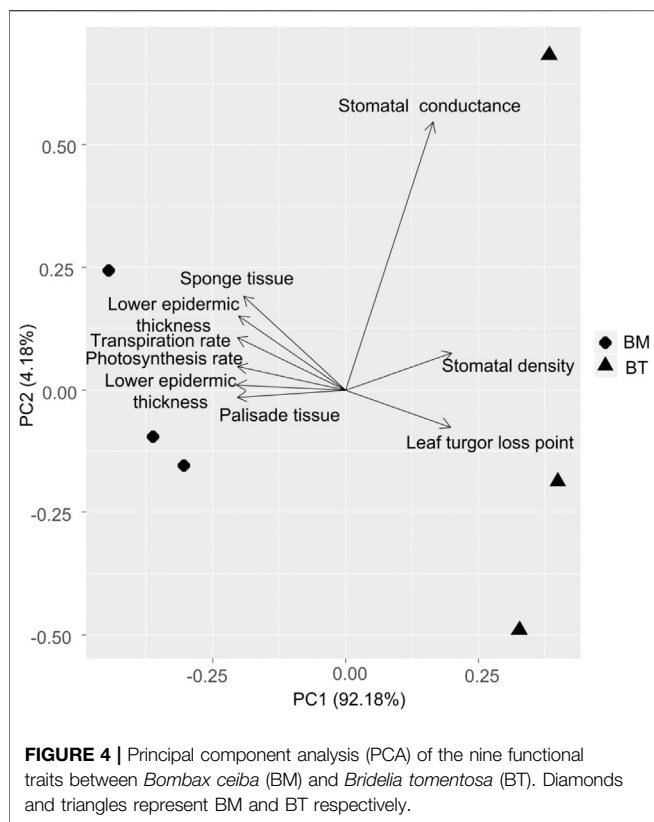


than *Bridelia tomentosa*, even though it had to face drought stress in the dry season. Higher photosynthesis rates will also result in higher leaf anatomy traits (He et al., 2017; Hua et al., 2017), stomatal traits (McAusland et al., 2016; Lawson and Vialet-Chabrand, 2019), and leaf transpiration rates (Santos et al., 2018). That was why we observed these traits for *Bombax ceiba* are all much higher (from 3 to 5 times) than those of *Bridelia tomentosa*. These results indicated that *Bombax ceiba* had developed appropriate functional traits to have very high growth rates even when facing the limited water supply.

We found that the mean precipitation in the dry season was merely 1/10th of that in the wet season, indicating high drought stress in the dry season. We also found *Bombax ceiba* in BPL had a much lower leaf turgor loss point than the native dominant plant species (*Bridelia tomentosa*) in the dry season. A lower leaf turgor loss point is usually observed when leaf cannot get enough water supply (Bartlett et al., 2012). Moreover, plants with a lower leaf turgor loss point can

maintain higher stomatal conductance, photosynthesis rates, and higher transpiration rates, when facing very limited water supply (Sack et al., 2003; Mitchell et al., 2008; Blackman et al., 2010). Thus, these results indicated that *Bombax ceiba* had developed higher drought stress tolerance than *Bridelia tomentosa* and thereby can maintain higher growth rates than *Bridelia tomentosa* even when facing the limited water supply. This also demonstrated that *Bridelia tomentosa* can even adapt better to the seasonal drought than the most dominant native species (*Bridelia tomentosa*) in the undisturbed tropical rainforest in the dry season.

Our PCA results revealed that *Bombax ceiba* and *Bridelia tomentosa* were significantly distinguished merely by stomatal conductance. *Bombax ceiba* had much lower stomatal conductance, compared to *Bridelia tomentosa*. Lower stomatal conductance is highly correlated with stomatal closure, which results in a lower leaf turgor point to tolerate drought stress (Brodrribb and Holbrook, 2003; Farrell et al., 2017; Trueba et al.,



2019). As a result, a higher intensity of stomatal closure in the dry season should be the key to help *Bombax ceiba* to possess higher drought stress tolerance and growth rates than the most dominant native tree species (*Bridelia tomentosa*) in the undisturbed tropical rainforest (Bartlett et al., 2012).

## CONCLUSION

Taken all results together, when planting *Bombax ceiba* to restore the highly degraded tropical forest in BPL, *Bombax ceiba* tends to trigger higher stomatal closure to have higher drought stress tolerance than the most dominant native tree species in the undisturbed tropical rainforest, thereby better adapting well to the drought stress in the dry season and having higher growth and survival rates. Moreover, consistent with previous observations (Stokes et al., 2009; Walker et al., 2009; Pang et al., 2018), mono-

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**Table 2 |** The first two axes of a principal component analysis (PCA) for *Bombax ceiba* and *Bridelia tomentosa*, based on nine plant traits. Bold indicates significant.

Functional traits	PC1	PC2
Upper epidermis thickness	-0.35	0.01
Palisade tissue thickness	-0.34	-0.02
Spongy tissue thickness	-0.33	0.28
Lower epidermis thickness	-0.34	0.24
Stomatal density	0.34	0.11
Transpiration rate	-0.34	0.17
Maximum photosynthesis rate	-0.34	0.07
<b>Stomatal conductance</b>	<b>0.28</b>	<b>0.90</b>
Leaf turgor loss point	0.34	-0.11

The traits include the upper epidermis thickness ( $\mu\text{m}$ ), palisade tissue thickness ( $\mu\text{m}$ ), spongy tissue thickness ( $\mu\text{m}$ ), lower epidermis thickness ( $\mu\text{m}$ ), stomatal density (numbers  $\text{mm}^{-2}$ ), transpiration rate ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), maximum photosynthesis rate ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), stomatal conductance ( $\text{mmol m}^{-2} \text{s}^{-1}$ ), and leaf turgor loss point (MPa).

planting fast-growing tree species (in our study, *Bombax ceiba*) with high survival rate can indeed help prevent landslides due to frequent typhoon and heavy rain. As a result, *Bombax ceiba* can indeed be a good candidate native species for performing reforestation to restore the degraded tropical rainforest in the whole Hainan Island, China.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

JL, WH, JY, KJ, and HZ designed the research. JL, WH, KJ, ZT, QH, and JC performed the research. ZT, QH, HZ, and JC analyzed the data. All authors have contributed to the writing of this manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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