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ORIGINAL PAPER

Morphometric study confirms the presence of only *Vatica mangachapoi* on Hainan Island, China

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Abstract To date only one species of the genus *Vatica* Linn. (Dipterocarpaceae) has been identified, and a subspecies and three varieties have been reported on Hainan Island, China. However, it remained controversial whether the species was *Vatica mangachapoi* or a new species *Vatica hainanensis*, and whether the subspecies or varieties are taxonomically valid. We evaluated here morphometric variations of 133 trees collected from nine populations and herbarium specimens of *Vatica* spp. using 16 traits of leaf and fruit. Among these, leaf traits varied more within and among populations than did fruit traits. Four traits of ratios were more stable than directly-measured traits within and among populations. The ranges of lamina length, lamina width and height of maximum lamina width point were the greatest among the 16 traits, while number of lateral veins varied least among the 12 directly-measured traits. Measurements from all 9 populations overlapped for each morphological trait, and variation of each trait was continuous among both individuals and populations. The range of variation did not distinguish any specimen from *V. mangachapoi* as described in the flora of Southeast Asia. By cluster analysis, individuals of each population as well as specimens of each variety formed no distinct clusters. The published varieties thus were characterized by no distinguishing variations in comparison with the nine sampled populations. In conclusion, the new species *V. hainanensis* as well as the subspecies and varieties were not supported by our comparisons, and only *V. mangachapoi* without any subspecies or varieties occurs on Hainan Island, China.

Keywords *Vatica* Linn. · *Vatica mangachapoi* · Morphological variability · Cluster analysis · Hainan Island

Introduction

Vatica mangachapoi is a dipterocarp species famous for its timber and non-wood byproducts. Its timber is important commercially in international tropical timber markets (Appanah and Turnbull 1998) and its leaves and stems contain a number of secondary metabolites that are used in perfumes and medicines (Qin et al. 2011). This species is widely distributed in Southeast Asia (Blanco 1837), and the populations of the genus *Vatica* Linn. (Dipterocarpaceae) on Hainan Island of China were first identified as *V. mangachapoi* (Qu 1956). Later, Wang (1985) treated the Hainan populations as a new species, *V. hainanensis* HT Chang et LC Wang, and subdivided it into two varieties, *V. hainanensis* var. *parvifolia* HT Chang apud LC Wang and *V. hainanensis* var. *glandipetala* LC Wang. Subsequently Yang et al. (2002) considered all Hainan populations as a subspecies of *V. mangachapoi* (*V. mangachapoi* spp. *hainanensis*). However, all these treatments were not

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accepted by Chen (2005) in *Flora of Guangdong* or by Li et al. (2007) in *Flora of China*, and only *V. mangachapoi* was considered to be native on Hainan Island. Nevertheless, a new variety, *V. mangachapoi* spp. *hainanensis* var. *wanningensis* Fu and Yang (2008), was described for populations growing on coastal sandy soils. These taxonomic studies did not quantify morphological variations at population level. The objectives of the present study were to quantify the variations of morphological characters within and among the populations of the taxa mentioned above and to determine their taxonomic validity.

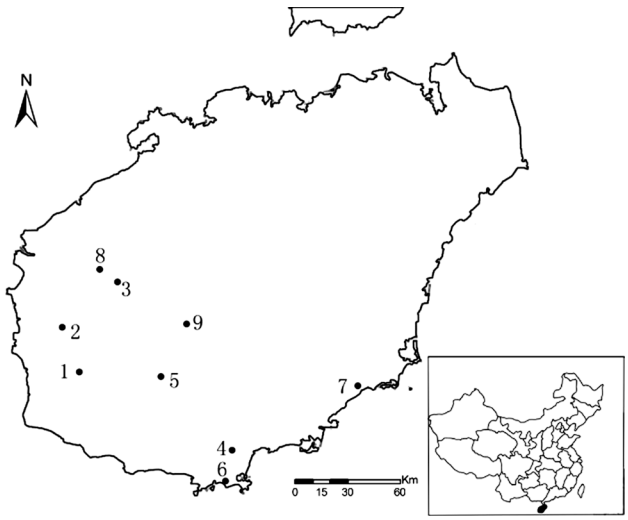

Fig. 1 Localities of nine natural populations of *Vatica* spp. on Hainan Island, China

Materials and methods

Sample collection

Nine populations of the genus *Vatica* were sampled on Hainan Island between 2011 and 2013 (Fig. 1; Table 1). Some were populations from which the type specimens of the new species, subspecies and varieties described above were collected. Six to thirty-four mature trees were randomly sampled in each population with the distances greater than 100 m between sampled trees. In total 133 individuals were sampled. For all sampled trees, morphological traits of leaf and fruit were measured (Table 2). Voucher specimens were deposited in Research Institute of Tropical Forestry (RITF), Chinese Academy of Forestry. Eighty-three herbarium specimens of the taxa mentioned above in South China Agricultural University Herbarium (CANT), Sun Yet-sen University Herbarium (SYS) and Chinese Academy of Forestry Herbarium (CAF) were also checked, and 11 specimens with fully-developed leaves and fruits were measured.

Morphological measurement

Species of *Vatica* are generally identified by their fruit sepal size, lamina size, lateral vein number, base form, and petiole length (Li et al. 2007). Twelve morphological characters of leaf and fruit were measured for each sampled tree and for specimens deposited in herbaria (Table 2). Thirty fruits and 15 completely developed leaves were measured for each sampled tree. On herbarium specimens, all fruits and fully developed leaves were measured. The

Table 1 Nine natural populations of *Vatica* spp. on Hainan Island, China

Populations		Latitude	Longitude	Altitude	MAAT	MAP	MATJU	MATJA	Soil type	Sample number
Code	Localities									
1	Jianfengling, Ledong County	18°43′	108°56′	270–460	24.5	1682	27.3	19.4	Latosol	14
2	Tuolie, Dongfang City	8°54′	108°51′	350–520	24.0	1240	27.2	19.1	Latosol	18
3	Bawangling, Changjiang County	17°07′	109°06′	400–500	23.6	1751	28.6	18.0	Latosol	6
4	Ganshiling, Sanya City	18°22′	109°39′	200–300	24.5	1200	28.0	20.0	Latosol	11
5	Kafaling, Ledong County	18°41′	109°17′	620–790	24.0	1559	26.3	17.2	Mountain yellow earth	17
6	Tropical Paradise Forest Park, Sanya City	18°15′	109°38′	290–430	25.5	1279	28.5	20.9	Latosol	8
7	Shimeiwan, Wanning City	18°39′	110°15′	5–70	24.5	2032	28.5	18.7	Coastal sandy soil	34
8	Wulie, Changjiang County	19°10′	109°00′	130–400	24.3	1676	29.3	18.7	Latosol	18
9	Wuzhishan, Wuzhishan City	18°56′	109°26′	420–570	22.5	1690	26.0	17.0	Lateritic red earth	7

MAAT mean annual air temperature; MAP mean annual precipitation; MATJU mean air temperature in July; MATJA mean air temperature in January

measurement accuracy was about 0.01 mm for length and width and 0.1° for angle of lamina base (Table 2). Ratios of the longest fruit sepal length to width, the shortest fruit sepal length to width, fruit length to diameter (width), and lamina length to width were calculated to roughly depict shapes of these organs (Frampton and Ward 1990).

Table 2 Traits measured in the present study

Traits	Abbreviation	Precision
Long fruit sepals length	LSL	0.01 mm
Long fruit sepals width	LSW	0.01 mm
Short fruit sepals length	SSL	0.01 mm
Short fruit sepals width	SSW	0.01 mm
Fruit height	FH	0.01 mm
Fruit width	FW	0.01 mm
Lamina length	LL	0.01 mm
Lamina width	LW	0.01 mm
Number of lateral vein	NLV	–
Angle of lamina base	ALB	0.1°
Height of maximum lamina width point	HMLW	0.01 mm
Petiole length	PL	0.01 mm
Ratio of long fruit sepals length to width	RLSLW	–
Ratio of short fruit sepals length to width	RSSLW	–
Ratio of fruit height to width	RFHW	–
Ratio of Lamina length to width	RLLW	–

Statistical analysis

Coefficients of variation (CV) for each trait were calculated within each population and among all nine populations to assess variability. The CV among populations was calculated based on the mean value of each population. Box and whisker plots were drawn for fruit and leaf measurements of each population to assess whether morphological variation was continuous. Software NTSYS version 2.1 was applied to calculate Nei's (1972) distances between individuals and generate a dendrogram of all sampled individuals and specimens by the neighbor joining method. FigTree version 1.3.1 was used to draw annular dendrogram.

Results

Of the 16 leaf and fruit traits measured, the angle of the lamina base (ALB) and height of maximum lamina width point (HMLW) showed in general the highest coefficients of variation (CV) within populations, and the ratio of fruit height to width (RFHW) the lowest (Table 3). Lower variances within populations were observed for fruit traits than for leaf traits. CV values were >20% for lamina length (LL), lamina width (LW) and HMLW in P5 and ALB in P9, while they were <6% for RFHW in all populations. The variances among populations for fruit traits were also

Table 3 Coefficients of variation for leaf and fruit traits in nine natural populations of *Vatica* spp. on Hainan Island, China

Traits	Within populations (%)									Among populations (%)
	P1	P2	P3	P4	P5	P6	P7	P8	P9	
LSL (mm)	16.87	10.15	6.38	8.75	11.57	12.34	14.81	18.22	15.95	6.34
LSW (mm)	12.47	11.66	7.55	12.09	16.14	14.21	14.28	16.13	13.39	7.71
SSL (mm)	12.42	15.14	8.66	10.76	12.49	16.17	15.06	11.11	12.53	8.34
SSW (mm)	16.87	10.15	6.38	8.75	11.57	12.34	14.81	18.22	15.95	6.36
FH (mm)	15.66	11.84	5.49	13.86	7.36	6.76	12.71	5.93	15.91	7.92
FW (mm)	15.7	13.17	7.91	14.21	9.11	6.93	13.57	6.06	17.35	8.97
RLSLW	11.05	8.47	6.83	13.04	11.31	9.48	10.12	13.29	13.17	4.72
RSSLW	12.17	10.66	11.51	11.76	12.07	9.3	13.63	16.95	15.15	5.43
RFHW	5.67	5.02	4.79	2.9	3.65	3.26	3.54	3.97	4.1	1.72
NLV	8.87	8.99	11.31	12.43	10.34	8.44	7.82	9.36	9.32	6.84
ALB (°)	12.16	16.79	17.95	16.94	15.78	10.63	13.75	12.2	25.73	8.98
LL (mm)	11.27	14.44	10.54	17.18	25.22	13.24	10.91	10.51	13.98	8.53
LW (mm)	14.43	11.76	11.16	15.39	21.03	11.27	11.4	10.82	9.4	5.64
PL (mm)	15.02	8.74	3.38	15.71	10.28	9.62	12.35	9.67	13.16	6.24
HMLW (mm)	12.51	16.91	12.51	22.44	24.63	11.12	13.9	10.33	15.38	7.79
RLLW	15.99	11.15	16.29	11.85	12.26	8.76	8.06	7.22	12.03	7.22

See Table 2 for abbreviations of traits

Table 4 Variation in leaf and fruit traits in nine natural populations of *Vatica* spp. on Hainan Island, China

Population	LSL (mm)			LSW (mm)			SSL (mm)			SSW (mm)			FH (mm)			FW (mm)			RLSLW			RSSLW		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
P1	42.44	22.36	68.43	11.30	7.54	17.27	16.52	10.06	28.24	4.48	2.74	6.21	5.87	3.76	9.41	5.56	3.62	8.94	3.76	2.39	4.70	3.67	2.46	4.86
P2	48.19	31.58	68.46	13.45	9.24	19.37	19.84	11.30	30.82	5.15	3.28	8.01	6.90	3.30	9.78	6.60	3.43	10.96	3.61	2.61	4.83	3.87	2.57	5.06
P3	44.78	32.91	59.67	13.17	9.59	17.49	16.02	10.74	21.42	5.07	3.63	6.93	7.32	5.53	8.99	6.93	4.09	9.44	3.42	2.48	4.43	3.19	2.16	4.51
P4	44.03	31.29	64.08	13.34	9.01	20.63	16.22	11.08	27.05	4.83	3.34	6.89	7.19	3.65	9.15	6.95	3.51	9.07	3.35	2.44	5.42	3.39	2.51	4.94
P5	42.27	27.19	68.24	12.11	6.38	19.78	17.78	10.85	27.09	4.95	3.41	7.69	6.89	4.75	9.25	6.61	4.30	9.14	3.54	2.27	4.71	3.62	2.11	5.15
P6	45.85	31.93	61.53	13.16	9.74	20.61	18.16	12.05	26.45	5.22	3.86	7.10	7.30	4.74	8.91	7.12	4.46	8.88	3.51	2.74	4.61	3.50	2.63	4.55
P7	50.63	29.75	75.57	14.43	8.61	22.41	19.90	11.70	32.02	5.49	3.04	8.69	6.69	4.09	10.16	6.44	3.42	10.00	3.53	2.66	5.19	3.65	2.34	5.55
P8	45.89	25.93	78.03	11.85	7.04	20.33	16.79	9.88	30.44	4.61	3.10	7.49	7.32	4.92	9.34	7.28	5.19	8.87	3.90	2.65	5.48	3.65	2.01	6.25
P9	42.28	27.77	60.67	12.10	8.41	15.82	17.02	12.61	22.44	4.79	3.49	6.40	6.08	4.30	8.97	5.75	4.06	8.44	3.53	2.61	4.47	3.61	2.22	4.65
All	46.19	22.36	78.03	12.98	6.38	22.41	18.11	9.88	32.02	5.02	2.74	8.69	6.82	3.30	10.16	6.57	3.42	10.96	3.60	2.27	5.48	3.62	2.01	6.25
Population	RFHW			NLV			ALB (°)			LL (mm)			LW (mm)			PL (mm)			HMLW (mm)			RLLW		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
P1	1.06	0.82	1.34	13.0	10	18	82.2	51.1	117.8	68.30	31.17	113.13	25.06	9.61	40.30	11.00	6.97	16.41	32.54	17.16	51.12	2.79	1.45	5.68
P2	1.05	0.83	1.34	12.9	8	17	75.4	44.9	134.2	67.64	36.87	104.05	24.03	12.71	38.47	10.96	6.09	17.36	34.89	15.59	61.05	2.84	1.81	3.90
P3	1.06	0.92	1.36	14.2	9	19	71.5	45.1	106.0	74.62	43.20	113.77	23.48	15.39	36.34	11.99	8.29	15.98	35.47	17.71	55.36	3.25	1.82	4.27
P4	1.04	0.91	1.28	13.2	9	20	83.7	50.2	132.9	73.91	42.53	142.16	26.81	13.47	47.60	11.83	6.86	20.83	37.87	18.72	78.44	2.78	1.88	3.99
P5	1.05	0.80	1.30	14.7	10	21	75.9	44.9	121.0	80.73	41.64	164.11	27.02	14.77	50.20	12.60	7.33	18.46	39.55	19.80	91.96	3.01	1.88	4.02
P6	1.03	0.90	1.21	12.2	8	16	89.0	59.5	119.1	61.15	36.98	100.55	24.98	13.37	38.00	10.68	5.99	16.65	30.67	16.27	47.78	2.47	1.83	3.37
P7	1.04	0.87	1.30	11.8	8	16	91.9	52.5	151.6	71.46	43.05	106.09	26.75	13.68	42.17	10.18	6.15	17.29	34.30	13.99	64.83	2.70	1.82	3.87
P8	1.01	0.87	1.24	12.8	8	19	73.8	48.6	125.1	68.64	42.88	99.43	23.93	15.08	35.99	11.16	5.35	16.78	34.67	20.41	52.40	2.89	2.05	4.04
P9	1.06	0.89	1.26	13.9	9	18	81.7	53.4	147.4	70.64	44.89	103.65	25.38	17.21	38.82	11.29	6.79	18.00	36.69	21.41	58.20	2.80	1.75	3.57
All	1.04	0.80	1.36	12.9	8	21	81.84	44.9	151.6	71.10	31.17	164.11	25.54	9.61	50.20	11.12	5.35	20.83	35.17	13.99	91.96	2.82	1.45	5.68

See Table 2 for abbreviations of traits

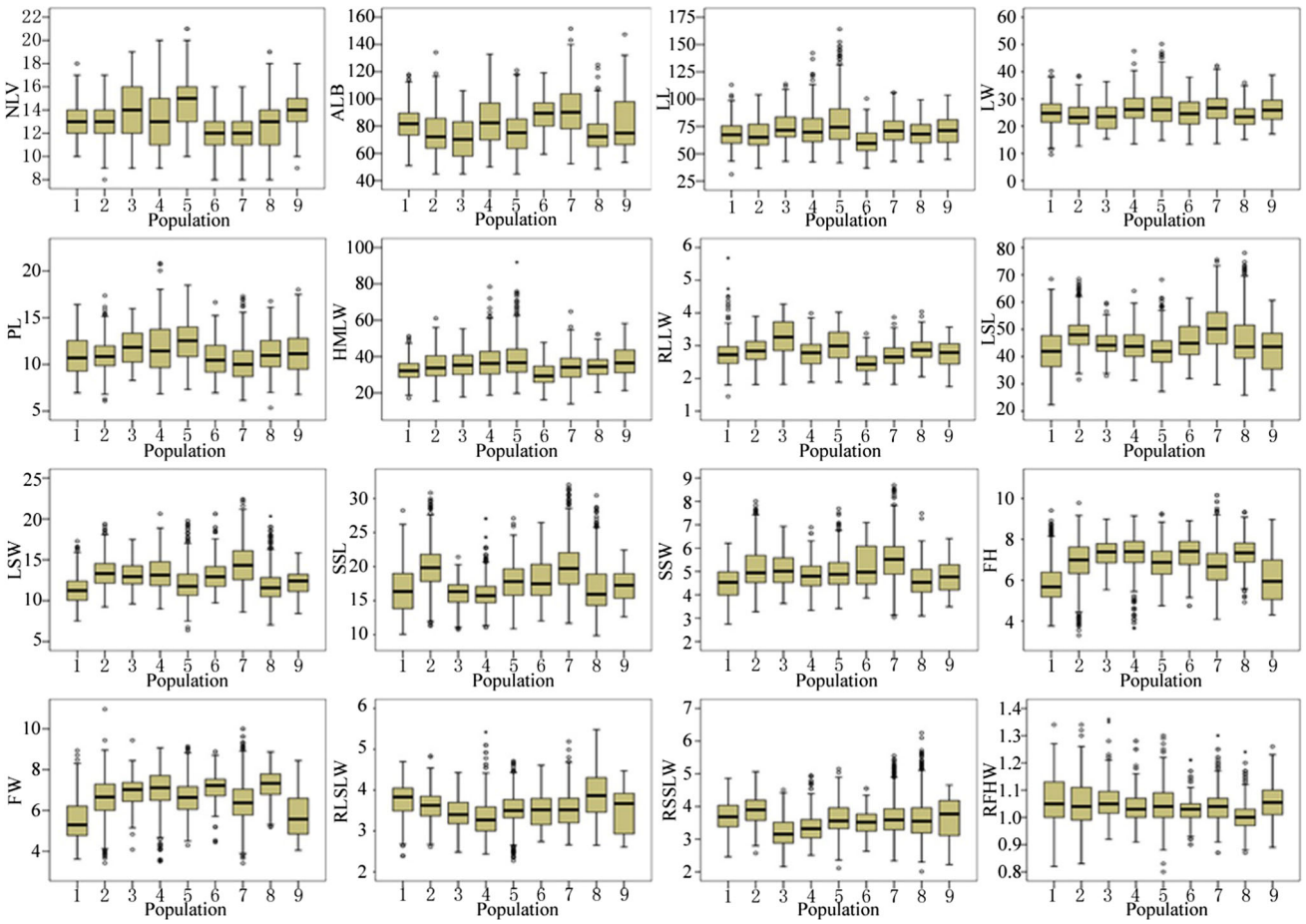

Fig. 2 *Box* and *whisker* plots showing the range of variation in fruit and leaf traits in the nine populations of *Vatica* spp. on Hainan Island, China. The *edges* of the *box* are 25% and 75%; the *vertical lines* are drawn from the box to the most extreme point within 1.5 interquartile ranges; and the *transverse lines* in box are the medians. See Table 1 for abbreviations of traits

lower than those for leaf traits: the CV of RFHW was <2%. As a whole, four ratio traits were less variable than size traits within as well as among populations.

For all samples of the nine populations, the variation ranges of LL, LW and HMLW were the greatest of the 16 traits and their maxima were above five times the minimum (Table 4). Meanwhile, RFHW varied least with its ratio of maximum to minimum being approximately 1.7. The number of lateral veins (NLV) was the least variable of 12 directly-measured traits. All nine populations overlapped considerably for each of 16 morphological traits. Variation of each morphological trait was continuous among individuals and populations (Fig. 2).

Cluster analysis shows the relationships between individuals among and within populations. Individuals of any population were not clearly distinguished from those of other populations and specimens of each variety did not cluster (Fig. 3; Table 5). From this we conclude that the published subspecific taxa possessed no morphological characters that distinguish them from *V. mangachapoi*.

Discussion

We quantified differences among individuals and populations for 16 morphological traits. Our results demonstrate that there are morphological variations among populations of the species. These might be caused by genetic variability, micro-scale adaptation or environmentally-induced differences (Schluter 2001; Alan 2002; Shi et al. 2009). We also documented by field survey that *Vatica spp.* showed abundant variation of leaf and fruit morphology at a range of sites from coastal sand to montane rain forest on Hainan Island.

To determine whether a species is a recognizable taxon, it is necessary to quantify its patterns of morphological variation and compare those to patterns displayed by its closest relatives (Hsu 1998). Nooteboom (1992) concluded that it is necessary to conduct field surveys and to study enough specimens ideally representing the entire geographic range of the subject taxon. Chang and Wang (Wang 1985) identified populations of *Vatica* on Hainan

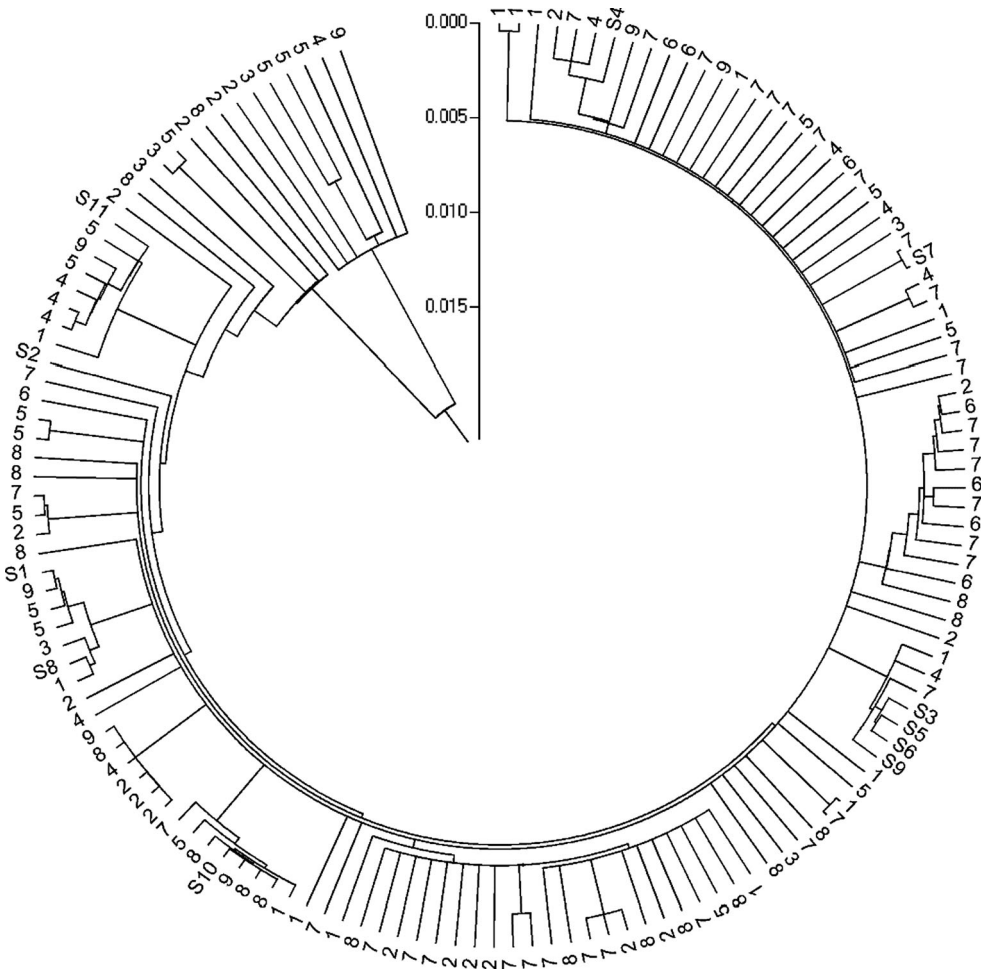

Fig. 3 Dendrogram at individual level generated from neighbor joining analysis based on Nei's (1972) distances for *Vatica* spp. on Hainan Island, China. *Note* 1–9, codes of the populations listed in Fig. 1, the same number means individuals from the same population; S1–S11, codes of specimens of taxa published; and particularly, S6–S11 were collected from trees in Guangdong Academy of Forestry, Guangzhou City (GAF) which were introduced from Bawangling, Changjiang County in 1960. See Table 5 in detail

Island as a new endemic species, *V. hainanensis,* rather than part of the variation within the widespread *V. mangachapoi*. They considered that the species of *Vatica* on Hainan Island was characterized as follows: NLE, 10–13; PL, 8–15 mm; LSL, 40–55 mm; LSW, 12–20 mm; SSL, 12–20 mm; SSW, 5–8 mm (Wang 1985). These measurements substantially differed from those of *V. mangachapoi* (NLE, 7–10; PL, 15–20 mm; LSL, 30–40 mm; LSW, 10–15 mm; SSL, 8 mm; SSW, 4 mm; Blanco 1837). In the present study on morphological variations of leaf and fruit traits of 133 individuals from nine populations, we found that the variation ranges of these traits were much wider (NLE, 8–21; PL, 5–21 mm; LSL, 22–78 mm; LSW, 6–22 mm; SSL, 10–32 mm; SSW, 3–9 mm). These measurements indicated that only SSL of the species on Hainan Island was obviously greater than that of *V. mangachapoi*, the ranges of NLE, PL, LSL, LSW and SSW found in the present study overlapped those described in the literature with both taxa identified. Since the study at population level yields a more accurate estimate of the variance within a taxon and is much more reliable than conclusions based on a small number of samples in herbaria (Nooteboom 1992; Hsu 1998), the two taxa could not be separated from each other. Our results suggest that all native populations of *Vatica* on Hainan Island are referable to *V. mangachapoi* without occurrence of subspecies because they are not distinguishable from the species described in *Flora de Filipinas* (Blanco 1837).

Our study also showed that each morphological trait showed continuous variation with a wide range on Hainan Island (Table 4; Fig. 2). The range of variation overlapped the reported measurements for var. *parvifolia* (LL: 40–60 mm; LW: 15–20 mm; LSL: 30–40 mm; and LSW: 8–10 mm) and var. *glandipetala* (LSL: 22–50 mm; LSW: 5–12 mm; and NLV: 6–9) published by Wang (1985) and Yang et al. (2002), and var. *wanningensis* (NLV: 8–9; and LSL: 45–52 mm) reported by Fu and Yang (2008) for each natural population. It is notable that the type specimen of variety *glandipetala* was collected from trees in Guangdong Academy of Forestry which were introduced from Bawangling, Hainan Island. Additionally, the presence of glands on the inner side of petal bases (Wang 1985) and indumentum differences on small branches (Fu and Yang 2008) are hardly sufficient differences for

Table 5 Detailed description of Fig. 3

Codes	Specimen	Localities	Taxa published	References	Sampled populations
S1, S2	Huang-quan 2726, 2725	Mihouling, Dongfang City	*Vatica hainanensis* HT Chang et LC Wang var. *parvifolia* HT Chang apud Wang; *Vatica mangachapoi* Blanco var. *parvifolia* (HT Chang) YK Yang et JK Wu	Wang (1985); Yang et al. (2002)	–
S3, S4	GA Fu 2024, 1984	Shimeiwan, Wanning City	*Vatica mangachapoi* Blanco var. *wanningensis* GA Fu et YK Yang	Fu and Yang (2008)	P7
S5	SK Lau 1903	Qicha Village, Changjiang County	*Vatica hainanensis* HT Chang et LC Wang; *Vatica mangachapoi* Blanco ssp. *hainanensis* (HT Chang et LC Wang) YK Yang et JK Wu	Wang (1985); Yang et al. (2002)	P3
S6	LC Wang 136	GAF	*Vatica hainanensis* HT Chang et LC Wang var. *glandipetala* LC Wang; *Vatica mangachapoi* Blanco var. *glandipetala* (LC Wang) YK Yang et JK Wu	Wang (1985); Yang et al. (2002)	P3
S7, S8, S9, S10	LC Wang 135, 134, 133, 131	GAF	*Vatica hainanensis* HT Chang et LC Wang var. *glandipetala* LC Wang	Wang (1985)	P3
S11	LC Wang 126	GAF	*Vatica hainanensis* HT Chang et LC Wang	Wang (1985)	P3

identifying variety *glandipetala* and *wanningensis*, respectively. Cluster analysis revealed that individuals in any population did not cluster, and specimens of a described taxon were assigned to the other taxa. This made it impossible to assign a given individual to any population based on these morphological traits. In other words, the varieties were poorly separated by cluster analysis based on Nei's (1972) distances. The three varieties, *parvifolia*, *glandipetala*, and *wanningensis*, could thus not be distinguished from one another or from the type specimens of *V. mangachapoi*.

Conclusion

The present study showed that all populations of *Vatica* on Hainan Island, China should be referred to *Vatica mangachapoi* with no subspecific categories being recognized. This conclusion supports the taxonomic treatment of the genus *Vatica* from Hainan Island as reported in *Flora of Guangdong* and *Flora of China*.

Taxonomic treatment

Vatica mangachapoi Blanco, Flora de Filipinas, ed.1, 401, 1837.

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