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Communication

Stem Carbon Dioxide Efflux of Lignophytes Exceeds That of Cycads and Arborescent Monocots

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Abstract: Tree stem CO_2 efflux (Es) can be substantial and the factors controlling ecosystem-level Es are required to fully understand the carbon cycle and construct models that predict atmospheric CO_2 dynamics. The majority of Es studies used woody lignophyte trees as the model species. Applying these lignophyte data to represent all tree forms can be inaccurate. The Es of 318 arborescent species was quantified in a common garden setting and the results were sorted into four stem growth forms: cycads, palms, monocot trees that were not palms, and woody lignophyte trees. The woody trees were comprised of gymnosperm and eudicot species. The Es did not differ among the cycads, palms, and non-palm monocots. Lignophyte trees exhibited Es that was 40% greater than that of the other stem growth forms. The Es of lignophyte gymnosperm trees was similar to that of lignophyte eudicot trees. This extensive species survey indicates that the Es from lignophyte tree species do not align with the Es from other tree growth forms. Use of Es estimates from the literature can be inaccurate for understanding the carbon cycle in tropical forests, which contain numerous non-lignophyte tree species.

Keywords: conservation physiology; secondary cambium; stem respiration

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1. Introduction

The efflux of carbon dioxide (CO_2) from tree stem surfaces (Es) has been extensively studied to answer various questions and more fully understand the global carbon cycle [1,2]. As with many aspects of biology research, the Es literature is biased toward one subset of biodiversity. Most case studies of tree Es have focused exclusively on lignophyte species with stems comprised mostly of wood constructed by true bifacial secondary cambium. This expansive literature contains only a few examples in which pachycaulous tree species with stems devoid of bifacial secondary cambium were represented [3–6].

A major contributor to Es is stem tissue respiration. However, numerous interacting factors coalesce to define Es in space and time. For example, CO_2 from root respiration can be transported to stems by way of xylem, and this CO_2 can exit xylem within stems to increase the Es above that of stem tissue respiration [7,8]. This transported CO_2 is under the influence of diel variations in sap flow [9,10]. The movement of CO_2 from the internal tissues to stem surfaces can also be under the control of temporal storage or re-fixation [11]. These and other interacting factors can cause the Es to be heavily influenced by CO_2 that was respired from tissues that are distant from the site of efflux [12].

A recent study designed to understand the diel patterns of Es for arborescent cycads, monocots, and lignophytes [6] included only six species of each growth form. Other studies that compared different stem tissue anatomy and its influence in Es were restricted to lignophyte species [13–15]. An extensive survey to compare the Es of trees with disparate stem growth forms has not been conducted to date in a single forest or garden. I hypothesized that Es from an extensive range of tree species would sort into significantly different groups, based on stem design. The objective of this study was to use the large living collection in a common garden setting to compare the Es of four growth forms used to design and construct tree stems.

2. Materials and Methods

This study was conducted at Nong Nooch Tropical Botanical Garden in Sattahip, Thailand. The location and characteristics of this living collection have been described [6]. The dates of measurements were 8–15 July 2019. In this setting and this time of year, the Es of non-lignophyte trees was not influenced by the time of day, but the lignophyte trees exhibited greater Es during midday [6]. Therefore, the measurements for this extensive species survey were restricted to the hours of 900–1500 h on each day of measurement.

A total of 99 cycad species were included (Table A1). There were 96 lignophyte species included (Table A2). The arborescent monocot species were separated into two groups. A total of 17 arborescent monocot taxa that were not palm species were included (Table A3). Finally, there were 106 palm species in the study (Table A4).

The Es was measured, as previously described [4–6]. Vigorous trees with no obvious wounds or decay on the stems were selected. A CIRAS EGM-4 analyzer fitted with a SRC-1 close system chamber (PP Systems, Amesbury, MA, USA) was used to quantify the Es from the stem surfaces. The chamber was secured using modeling clay as the sealant at a stem height of 30–40 cm above the root collar. The EGM-4 recorded the air temperature, and the chamber's increase in CO_2 concentration above ambient was quantified after a 2 min period. The change in CO_2 concentration was used to calculate the flux by dividing by area and time. Three periods of efflux were recorded at different radial locations for each sampling period for each tree.

The stem surface temperature was measured with an infrared thermometer (Milwaukee Model 2267-20, Milwaukee Tool, Brookfield, WI, USA). The relative humidity was determined with a sling psychrometer every hour during the periods of measurements. The stem diameter at the height of measurements and total stem height were measured for each tree.

Two sampling periods were applied to each species. For taxa with more than one large tree, this included two trees. For taxa with a single large tree, the two samples were from the same tree but separated by at least three days. The data were sorted according to four stem growth forms: cycad species, palm species, arborescent non-palm monocot species, and lignophyte species. The data were subjected to ANOVA using the PROC MIXED model (SAS Institute, Cary, NC, USA) with unequal replications. There were 636 observations in the data set, two per species. The two observations were treated as subsamples in the analysis. The means separation was conducted by Tukey's HSD test.

3. Results and Discussion

The cycad trees were represented by 53 Cycadaceae and 46 Zamiaceae species (Table A1). The stem circumference ranged from 51–169 cm with a mean of 96 cm. The mean stem temperature was 31.8 °C and the concomitant mean air temperature was 32.6 °C. Individual Es measurements ranged from 0.5–6.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The lignophyte trees were represented by 34 families (Table A2). The stem circumference ranged from 51–156 cm with a mean of 84 cm. The mean stem temperature was 31.3 °C and concomitant mean air temperature was 32.0 °C. Individual Es measurements ranged from 0.2–7.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The monocot trees that were not palm species were represented by five families (Table A3). The stem circumference ranged from 51–175 cm with a mean of 82 cm. The mean stem temperature was 31.5 °C and the concomitant mean air temperature was 32.1 °C. The individual Es measurements range from 0.8–4.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The palm species representing the Arecaceae family exhibited a stem circumference ranging from 48–182 cm with a mean of 71 cm (Table A4). The mean stem temperature was 31.7 °C and the concomitant mean air temperature was 32.4 °C. The individual Es measurements ranged from 0.7–7.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The relative humidity ranged from 56% to 69% and did not change substantially among the hours and dates of the study.

The stem CO_2 efflux differed among the four stem growth forms ($F_{3,314} = 10.64$, $p < 0.001$). The means separated into two groups, with the lignophyte species exhibiting greater Es than the other three stem growth forms (Table 1). The lignophyte trees exhibited

Es that was 40% greater than the mean of the other growth forms. No differences in the Es occurred among the cycad, palm, and non-palm monocot stem forms.

Table 1. Stem carbon dioxide efflux ($\mu mol \cdot m^{-2} \cdot s^{-1}$) of arborescent species as influenced by the stem growth form.

Stem Growth Form	n	Efflux
Lignophyte [1]	96	3.421 ± 0.140 a [2]
Palm	106	2.593 ± 0.133 b
Cycad	99	2.415 ± 0.138 b
Monocot (non-palm)	17	2.321 ± 0.332 b

[1] The lignophyte species were eudicot and gymnosperm trees that produce true wood from secondary bifacial vascular cambium. [2] Growth form with the same letter not different according to Tukey's HSD test.

Cycads and monocot trees often produce thick primary growth constructed by a primary thickening meristem, and do not possess bifacial secondary cambium to increase stem diameter at distances away from the stem tip [16–22]. For all of these trees, the peripheral tissues are ground tissue with vascular tissues embedded closer to the stem center. One of the factors that influences CO_2 efflux from a stem surface is the diffusion and conductance constraints imposed by tissues that are peripheral to tissues that serve as the greatest internal source of CO_2, such as sap flow in xylem [23]. The substantial radial distance of xylem tissues and other major sources of CO_2 from the stem surface of these pachycaulous trees can account for the greater mean Es for lignophyte trees, which has been shown herein.

Considering the prominence of these pachycaulous trees in tropical forests, the historical exclusion of them from Es studies is unfortunate. Indeed, the CO_2 derived from stem efflux can represent up to 40% of the CO_2 contributed to by vegetation [1,24]. This survey, represented by 222 pachycaulous tree species, confirms the earlier findings based on a limited number of species [6], and indicates that attempts to use the Es literature based on the lignophyte species can over-estimate the Es in regions that are represented by these tree species.

Cycads comprise the most threatened contemporary plant group [25]. Conservation physiology has emerged as a critical component of the suite of conservation strategies, because an understanding of the physiological responses of threatened organisms to their escalating biotic and abiotic threats is required for successful species recovery [26,27]. For federally listed endangered cycad species in the United States, such as *Cycas micronesica* K.D. Hill (see Table A1), understanding the physiology of the taxa is crucial for developing effective federal recovery plans [28]. Clearly, the pursuit of more cycad physiology studies will advance the nascent discipline of conservation physiology.

Future research on the Es of cycad and monocot trees will be required to fully understand the reasons that mean Es is less than the mean Es of lignophyte trees. The design of cycad stems is fairly homogeneous, with vascular cylinders inserted between the persistent living pith and cortex [29]. The design of palm stems is also fairly homogeneous with vascular bundles scattered through the ground tissue [19,22]. However, the design of the non-palm arborescent monocot tree stems is heterogeneous among the families. A closer look at this group of pachycaulous species can yield interesting findings about what endogenous factors mostly control the Es of these non-lignophyte trees.

In conclusion, the many factors that interact to control the magnitude of CO_2 efflux from tree stem surfaces are differentially expressed among various tree stem designs. The results herein suggest that the traits of stem peripheral tissues can be among the defining factors that cause the differences in Es among various tree growth forms.

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Appendix A

Table A1. List of cycad species included in the carbon dioxide efflux study. Circ = circumference, Air T = air temperature, and Stem T = surface temperature of stems.

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Ceratozamia delucana Vázq.Torres, A.Moretti and Carvajal-Hern.	Zamiaceae	84	32	32.9	2.6222	2.3290
Ceratozamia latifolia Miq.	Zamiaceae	72	31	32.9	2.3227	2.0197
Ceratozamia robusta Miq.	Zamiaceae	112	31	33.1	2.2501	1.9566
Cycas angulata R.Br.	Cycadaceae	107	32	32.8	5.7745	5.1166
Cycas apoa K.D.Hill	Cycadaceae	76	33	32.5	4.8633	4.2288
Cycas badensis K.D.Hill	Cycadaceae	82	32	31.1	1.7512	1.5148
Cycas beddomei Dyer	Cycadaceae	78	33	31.7	1.7819	1.5508
Cycas bougainvilleana K.D.Hill	Cycadaceae	65	32	31.1	4.1522	3.6103
Cycas cairnsiana F.Muell.	Cycadaceae	101	31	31.4	2.0749	1.8051
Cycas campestris K.D.Hill	Cycadaceae	93	32	30.4	2.4442	2.1251
Cycas chamaoensis K.D.Hill	Cycadaceae	101	32	31.8	1.8463	1.5969
Cycas changjiangensis N.Liu	Cycadaceae	81	33	31.7	1.0225	2.2722
Cycas clivicola K.D.Hill	Cycadaceae	87	33	31.7	2.0377	1.7805
Cycas couttsiana K.D.Hill	Cycadaceae	95	33	32.1	0.9089	1.1361
Cycas curranii (J.Schust.) K.D.Hill	Cycadaceae	103	32	30.1	5.1493	4.4800
Cycas debaoensis Y.C.Zhong and C.J.Chen	Cycadaceae	110	32	30.9	1.5203	1.3191
Cycas diannanensis Z.T.Guan and G.D.Tao	Cycadaceae	84	33	32.1	5.6678	4.9231
Cycas edentata de Laub.	Cycadaceae	68	32	29.8	1.9212	1.6663
Cycas elongata (Leandri) D.Y.Wang	Cycadaceae	103	32	31.9	2.1460	1.7042
Cycas falcata K.D.Hill	Cycadaceae	89	33	31.8	2.8403	1.4517
Cycas furfuracea W.Fitzg.	Cycadaceae	108	34	34.5	2.5564	2.2217
Cycas glauca Miq.	Cycadaceae	92	33	32.2	4.0045	3.5346
Cycas hainanensis C.J.Chen ex C.Y.Cheng, W.C.Cheng and L.K.Fu	Cycadaceae	91	33	31.4	2.5496	2.2217
Cycas hongheensis S.Y.Yang and S.L.Yang	Cycadaceae	82	32	30.8	2.2847	2.1165
Cycas inermis Lour.	Cycadaceae	109	33	32.1	6.1934	5.4154
Cycas javana (Miq.) de Laub.	Cycadaceae	112	33	32.7	2.7945	2.4300
Cycas macrocarpa Griff.	Cycadaceae	75	31	31.2	4.1164	3.6103
Cycas media R.Br.	Cycadaceae	82	33	31.9	2.1964	1.8996
Cycas megacarpa K.D.Hill	Cycadaceae	62	33	31.8	2.1114	1.8380
Cycas micronesica K.D.Hill	Cycadaceae	62	33	32.5	1.3764	1.1992
Cycas nathorstii J.Schust.	Cycadaceae	102	32	31.9	1.7446	1.5148
Cycas nongnoochiae K.D.Hill	Cycadaceae	88	33	31.9	2.9513	2.5689
Cycas ophiolitica K.D.Hill	Cycadaceae	115	33	32.1	1.1846	1.0225
Cycas pachypoda K.D.Hill	Cycadaceae	98	32	30.8	4.4112	3.8482
Cycas papuana F.Muell.	Cycadaceae	86	31	30.7	5.3312	4.6517
Cycas pectinata Buch.-Ham.	Cycadaceae	93	32	33.4	2.0547	1.7805
Cycas petrae A.Lindstr. and K.D.Hill	Cycadaceae	69	33	32.1	1.7965	2.3353
Cycas platyphylla K.D.Hill	Cycadaceae	116	33	31.7	0.6817	1.5905
Cycas pranburiensis Yang, Tang, Hill and Vatcharakorn	Cycadaceae	78	33	32.5	1.5115	1.3210
Cycas revoluta Thunb.	Cycadaceae	85	32	32.8	2.2223	1.9314

Table A1. *Cont.*

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Cycas riuminiana Porte ex Regel	Cycadaceae	65	33	33.1	3.7784	3.2821
Cycas rumphii Miq.	Cycadaceae	84	30	32.1	4.0561	3.5346
Cycas seemannii A.Br.	Cycadaceae	63	32	31.1	3.0296	2.1523
Cycas semota K.D.Hill	Cycadaceae	84	33	30.2	3.4865	3.0296
Cycas shanyaensis G.A.Fu	Cycadaceae	68	32	32.1	2.4690	3.0296
Cycas siamensis Miq.	Cycadaceae	79	32	31.9	3.4431	2.9867
Cycas silvestris K.D.Hill	Cycadaceae	69	33	32.2	1.6679	1.4517
Cycas sphaerica Roxb.	Cycadaceae	92	32	30.4	3.4155	2.9867
Cycas taitungensis Shen, Hill, Tsou and Chen	Cycadaceae	83	32	31.8	4.4478	3.8880
Cycas tansachana K.D.Hill and S.L.Yang	Cycadaceae	113	33	31.8	1.1864	1.0099
Cycas thouarsii R.Br.	Cycadaceae	82	31	30.9	1.1968	1.0225
Cycas tropophylla K.D.Hill and P.K.Lôc	Cycadaceae	94	33	32.1	2.0312	1.7673
Cycas tuckeri K.D.Hill	Cycadaceae	95	32	30.8	1.7157	1.4933
Cycas wadei Merr.	Cycadaceae	83	32	31.3	2.1113	1.8380
Cycas yorkiana K.D.Hill	Cycadaceae	94	33	32.1	2.1564	1.8746
Cycas zeylanica (J.Schust.) A.Lindstr. and K.D.Hill	Cycadaceae	78	33	30.8	2.3312	2.0103
Dioon argenteum Gregory, Chemnick, Salas-Morales and Vovides	Zamiaceae	93	33	31.1	4.9455	4.4308
Dioon caputoi De Luca, Sabato and Vázq.Torres	Zamiaceae	91	32	34.8	2.4857	2.1523
Dioon edule Lindl.	Zamiaceae	155	32	33.1	3.7795	3.2821
Dioon mejiae Standl. and L.O. Williams	Zamiaceae	98	33	31.6	1.9594	1.7042
Dioon merolae De Luca, Sabato and Vázq.Torres	Zamiaceae	110	32	32.7	4.9132	4.2920
Dioon spinulosum Dyer ex Eichl.	Zamiaceae	91	33	32.2	2.2561	1.9566
Encephalartos aemulans Vorster	Zamiaceae	138	33	31.9	4.4466	3.9976
Encephalartos altensteinii Lehm.	Zamiaceae	116	34	32.2	2.2504	2.4679
Encephalartos arenarius R.A.Dyer	Zamiaceae	97	33	32.2	1.4495	1.5905
Encephalartos bubalinus Melville	Zamiaceae	125	33	31.7	1.0569	1.1614
Encephalartos chimanimaniensis R.A.Dyer and I.Verd.	Zamiaceae	121	33	31.8	1.5948	1.7420
Encephalartos concinnus R.A.Dyer and Verdoorn	Zamiaceae	114	33	32.1	4.9765	5.4465
Encephalartos dyerianus Lavranos and D.L.Goode	Zamiaceae	124	34	32.9	3.5004	3.8501
Encephalartos equatorialis P.J.H.Hurter	Zamiaceae	127	34	32.9	1.7764	1.9314
Encephalartos eugene-maraisii Verd.	Zamiaceae	116	33	32.1	2.2465	2.4679
Encephalartos inopinus R.A.Dyer	Zamiaceae	121	34	32.2	2.3611	2.5878
Encephalartos lebomboensis I.Verd.	Zamiaceae	97	33	32.3	1.6564	1.8146
Encephalartos mackenziei L.E.Newton	Zamiaceae	111	33	32.2	0.8645	0.9089
Encephalartos macrostrobilus S.Jones and Wyants	Zamiaceae	125	34	32.8	1.7946	1.9566
Encephalartos manikensis (Gilliland) Gilliland	Zamiaceae	133	33	31.7	1.5946	1.7420
Encephalartos msinganus Vorster	Zamiaceae	108	33	32.1	2.9764	3.2663
Encephalartos munchii R.A.Dyer and I.Verd.	Zamiaceae	134	33	32.2	2.3331	2.5562
Encephalartos natalensis R.A.Dyer and I.Verd.	Zamiaceae	109	34	32.9	1.1915	1.3065
Encephalartos paucidentatus Stapf and Burtt Davy	Zamiaceae	120	33	32.5	1.7764	1.9314
Encephalartos princeps R.A.Dyer	Zamiaceae	113	33	32.8	2.0645	1.8947
Encephalartos pterogonus R.A.Dyer and I.Verd.	Zamiaceae	119	33	33.1	2.4465	2.6986
Encephalartos sclavoi De Luca, D.W.Stev. and A.Moretti	Zamiaceae	101	33	32.1	1.5959	1.7420
Encephalartos senticosus Vorster	Zamiaceae	107	32	30.9	0.8465	0.8710
Encephalartos septentrionalis Schweinf.	Zamiaceae	119	34	32.9	1.6694	3.7239
Encephalartos tegulaneus Melville	Zamiaceae	124	33	32.1	3.6915	4.0647
Encephalartos transvenosus Stapf and Burtt Davy	Zamiaceae	128	33	31.2	4.5121	4.9357
Encephalartos whitelockii P.J.H.Hurter	Zamiaceae	163	32	31.1	2.7154	2.9865
Lepidozamia hopei (W.Hill) Regel	Zamiaceae	64	32	29.1	1.4896	1.2623
Lepodozamia peroffskyana Regel	Zamiaceae	92	32	33.8	1.6765	1.8304

Table A1. *Cont.*

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Macrozamia moorei F.Muell.	Zamiaceae	169	32	32.7	1.8686	1.6663
Microcycas calocoma (Miq.) A.DC.	Zamiaceae	91	32	32.1	2.0644	1.8304
Zamia elegantissima Schutzman, Vovides and R.S.Adams	Zamiaceae	51	33	30.9	1.3312	1.4517
Zamia furfuracea L.f.	Zamiaceae	91	33	32.1	1.7154	1.8746
Zamia gentryi Dodson	Zamiaceae	63	33	30.5	2.0105	2.1999
Zamia imperialis A.S.Taylor, J.L.Haynes and Holzman	Zamiaceae	59	32	31.1	1.3866	1.5148
Zamia lindenii Regel ex André	Zamiaceae	78	30	29.9	2.0166	2.1998
Zamia obliqua A.Braun	Zamiaceae	51	32	30.2	2.7626	2.9965
Zamia skinneri Warsc.	Zamiaceae	58	32	30.2	2.3465	2.5765

Table A2. List of the lignophyte species included in the carbon dioxide efflux study. Circ = circumference, Air T = air temperature, and Stem T = surface temperature of stems.

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Acacia auriculiformis A.Cunn. Ex Benth.	Fabaceae	92	32	29.3	3.5566	3.7944
Adansonia digitata L.	Malvaceae	71	31	31.4	3.9465	3.5346
Adansonia madagascariensis Baill.	Malvaceae	69	33	32.3	2.0566	1.8304
Afrocarpus gracilior (Pilg.) C.N. Page	Podocarpaceae	72	32	31.3	6.4465	6.3748
Agathis dammara (Lamb.) Rich.	Araucariaceae	85	33	32.2	2.3465	2.5698
Agathis moorei (Lind.) Mast.	Araucariaceae	52	33	30.9	1.3255	1.8304
Agathis robusta (C.Moore ex F.Muell.) Bailey	Araucariaceae	55	32	30.9	1.7198	1.8935
Albizia saman (Jacq.) Merr.	Fabaceae	156	32	30.6	1.2765	1.3886
Amherstia nobilis Wall.	Fabaceae	68	32	31.4	2.1894	1.9566
Annona squamosa L.	Annonaceae	62	31	30.8	1.6768	1.8746
Araucaria bidwillii Hook.	Araucariaceae	91	32	31.2	5.0032	4.4813
Araucaria columnaris J.R.Forst. Hook	Araucariaceae	69	30	30.2	6.2264	5.6237
Araucaria cunninghamii Mudie	Araucariaceae	58	31	29.4	2.3631	2.0829
Araucaria heterophylla (Salisb.) Franco	Araucariaceae	96	32	33.2	2.8403	2.7771
Araucaria luxurians (Brongn. and Grisb.) de Laub.	Araucariaceae	64	31	30.1	6.0021	5.4281
Araucaria montana Brong. and Gris	Araucariaceae	54	32	31.8	2.9034	2.6643
Araucaria nemorosa de Laub.	Araucariaceae	93	33	31.8	2.0829	2.0197
Artocarpus altilis (Parkinson) Fosberg	Moraceae	88	33	32.1	3.6625	3.9986
Artocarpus heterophyllus Lam.	Moraceae	74	31	30.8	2.4689	2.7140
Averrhoa bilimbi L.	Oxalidaceae	72	33	32.3	4.2165	4.6647
Averrhoa carambola L.	Oxalidaceae	69	31	30.1	4.4465	3.9865
Bougainvillea sp. Comm. Ex Juss.	Nyctaginaceae	51	33	32.1	1.9955	2.1133
Brachychiton acerifolius (A.Cunn ex G.Don) F.Muell.	Malvaceae	53	31	31.7	2.2566	2.0134
Brachychiton rupestris (T.Mitch. Ex Lindl.) K.Schum.	Malvaceae	54	30	30.3	4.4656	4.0269
Bursera simaruba (L.) Sarg.	Burseraceae	51	32	30.8	0.8119	0.9026
Callistemon viminalis (Sol. Ex Gaertn.) G.Don	Myrtaceae	77	30	30.7	6.0022	5.4154
Callistris baileyi C.T. White	Cupressaceae	59	31	30.8	2.6644	2.3984
Calophyllum sil Lauterb.	Clusiaceae	103	30	30.9	3.3186	3.0107
Cananga odorata (Lam.) Hook.f. and Thomson	Annonaceae	121	32	31.1	4.4212	4.8766
Casuarina equisitifolia L.	Casuarinaceae	102	33	33.4	3.5564	3.8965
Cavanillesia hylogeiton Ulbr.	Malvaceae	111	33	32.8	2.8845	2.5562
Cecropia obtusifolia Bertol.	Urticaceae	88	31	30.3	5.1114	4.6012
Cecropia peltata L.	Urticaceae	113	32	31.6	3.6266	3.2265
Ceiba pentandra (L.) Gaertn.	Malvaceae	123	33	31.9	4.3489	3.9196
Clusia rosea Jacq.	Clusiaceae	61	33	31.3	3.1153	3.5642
Delonix decaryi (R.Vig.) Capuron	Fabaceae	82	32	31.7	1.3349	1.1992

Table A2. *Cont.*

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Delonix regia (Hook.) Raf.	Fabaceae	72	32	31.2	3.6644	3.2947
Dimocarpus longan Lour.	Sapindaceae	126	33	32.3	2.8844	2.5649
Diospyros discolor Willd.	Ebenaceae	129	33	31.7	0.5116	0.4418
Diospyros nigra (J.F.Gmel.) Perrier	Ebenaceae	99	30	28.9	4.1445	4.5444
Elaeocarpus hygrophilus Kurz	Elaeocarpaceae	53	31	30.8	3.9787	3.5699
Euphorbia kamponii Rauh and Petignat	Euphorbiaceae	53	33	33.2	1.1899	1.3065
Euphorbia laeta Aiton	Euphorbiaceae	81	34	33.5	4.8011	4.2920
Fernandoa madagascariensis (Baker) A.H.Gentry	Bignoniaceae	51	31	30.3	2.0645	1.8304
Ficus benjamina L.	Moraceae	151	30	29.8	3.2233	2.9034
Ficus elastica Roxb. ex Hornem.	Moraceae	94	33	32.2	3.6151	3.2663
Ficus lyrata Warb.	Moraceae	104	32	31.4	6.1184	5.8793
Ficus natalensis Hochst.	Moraceae	56	31	29.8	5.6112	5.0083
Garcinia cymosa (K.Schum.) I.M.Turner and P.F.Stevens	Clusiaceae	64	32	31.3	3.2311	2.9760
Guaiacum officinale L.	Zygophyllaceae	74	32	30.5	4.3365	3.8956
Inga edulis Mart.	Fabaceae	64	33	32.2	1.0848	0.9650
Kopsia arborea Blume	Apocynaceae	78	31	30.8	1.1323	0.9976
Lagerstroemia indica L.	Lythraceae	66	33	31.9	5.7112	5.1125
Lagerstroemia speciosa (L.) Pers.	Lythraceae	78	33	32.1	6.3054	5.6616
Leucaena leucocephala (Lam.) de Wit	Fabaceae	51	32	30.8	2.0202	2.2091
Litsea elliptica Blume	Lauraceae	62	32	31.3	2.1132	1.8935
Magnolia × *alba* (D.C.) Figlar	Magnoliaceae	145	32	31.8	1.6650	1.5148
Mallotus barbatus Müll.Arg.	Euphorbiaceae	82	30	30.3	5.7765	5.1347
Mangifera foetida Lour.	Anacardiaceae	57	33	33.4	7.4986	6.9429
Mangifera indica L.	Anacardiaceae	61	33	33.5	4.0065	3.5847
Melaleuca bracteata F. Muell.	Myrtaceae	96	31	30.2	1.0065	1.4466
Morinda citrifolia L.	Rubiaceae	61	30	30.7	1.3389	1.4678
Moringa hildebrandtii Eng.	Moringaceae	82	32	31.2	4.1132	3.6608
Moringa oleifera Lam.	Moringaceae	75	33	32.1	0.2211	0.1894
Muntingia calabura L.	Muntingiaceae	66	32	31.1	1.5644	1.3886
Nephelium lappaceum L.	Sapindaceae	128	33	32.3	1.8686	1.6663
Nerium oleander L.	Apocynaceae	52	32	30.8	1.2234	1.1321
Pachira aquatica Aub.	Malvaceae	105	33	32.1	2.0044	1.7988
Pachira insignis (Sw.) Savigny	Malvaceae	95	30	30.6	5.2123	5.8068
Persea americana Mill.	Lauraceae	126	33	32.5	1.5590	1.3232
Phyllanthus acidus (L.) Skeels	Phyllanthaceae	86	32	31.1	1.4391	1.5565
Pithecellobium dulce (Roxb.) Benth.	Fabaceae	96	32	31.8	1.6265	1.4517
Plumeria rubra L.	Apocynaceae	73	33	31.6	5.3795	5.9764
Podocarpus neriifolius D.Don	Podocarpaceae	85	30	29.8	4.3035	4.7965
Polyalthia longifolia (Sonn.) Thwaites	Annonaceae	93	33	32.1	3.1138	2.7105
Pouteria campechiana (Kunth.) Baehni	Sapotaceae	138	32	30.7	1.1133	2.0197
Pseudobombax septenatum (Jacq.) Dugand	Malvaceae	66	31	30.7	0.9922	0.8836
Psidium guajava L.	Myrtaceae	52	30	30.8	4.9597	5.5416
Robinia hispida L.	Fabaceae	66	33	31.8	2.4465	2.2247
Sandoricum koetjape (Burm.f.) Merr.	Meliaceae	141	33	32.1	1.9322	1.7042
Saraca asoca (Roxb.) Willd.	Fabaceae	72	31	30.3	4.1645	4.5679
Saraca declinata Miq.	Fabaceae	75	32	30.1	3.0111	3.3452
Saraca thaipingensis Prain	Fabaceae	89	31	30.7	1.0946	1.1992
Schizolobium parahyba (Vll.) S.F.Blake	Fabaceae	91	32	31.1	0.9955	0.8836
Senegalia polyacantha (Willd.) Siegler and Ebinger	Fabaceae	81	33	31.8	3.7989	4.2265
Sterculia foetida L.	Malvaceae	141	33	32.4	3.4844	3.8877
Syzygium cumini (L.) Skeels	Myrtaceae	151	32	30.2	4.6075	3.9764
Syzygium forte (F.Muell.) B.Hyland	Myrtaceae	113	31	31.5	1.2134	1.3255
Syzygium malaccense (L.) Merr. and L.M.Perry	Myrtaceae	91	33	31.8	2.2233	2.4616

Table A2. *Cont.*

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Tamarindus indica L.	Fabaceae	119	33	32.2	6.6644	7.5740
Tecoma stans Griseb.	Bignoniaceae	61	33	31.9	2.1645	2.3984
Tectona grandis L.f.	Lamiaceae	65	33	32.2	0.6566	0.6943
Terminalia catappa L.	Combretaceae	53	30	30.5	2.4844	2.7771
Terminalia ivorensis A.Chev.	Combretaceae	69	33	31.9	3.5467	3.9865
Triplaris americana L.	Polygonaceae	97	32	31.1	2.5546	2.8403
Xanthostemon chrysanthus (F.Muell.) Benth.	Xanthorrhoeaceae	96	33	32.2	3.6134	4.0395

Table A3. List of non-palm arborescent monocot species included the in carbon dioxide efflux study. Circ = circumference, Air T = air temperature, and Stem T = surface temperature of stems.

Species	Family	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Beaucarnea recurvata Lem.	Asparagaceae	84	31	30.2	3.1848	2.8466
Dasylirion wheeleri S.Watson ex Rothr.	Asparagaceae	99	33	32.6	4.4489	4.0032
Dracaena cochinchinensis (Lour.) S.C.Chen	Asparagaceae	117	32	31.5	2.9441	2.6509
Dracaena dereminis Engl.	Asparagaceae	58	33	32.5	1.2234	1.0730
Dracaena floribunda Baker	Asparagaceae	101	33	32.2	2.0498	1.8304
Dracaena fragrans (L.) Ker Gaw.	Asparagaceae	66	33	32.1	3.4899	3.0927
Ensete ventricosum (Welw.) Cheesman	Musaceae	175	33	31.8	4.7003	4.2099
Musa x paradisiaca L.	Musaceae	75	31	30.5	2.4468	2.6798
Pandanus dubius Spreng.	Pandanaceae	73	32	31.7	3.5564	3.9888
Pandanus rabaiensis Rendle.	Pandanaceae	64	33	32.1	3.9166	3.4714
Pandanus tectorius Parkinson ex Du Roi	Pandanaceae	71	31	31.2	3.0865	3.4470
Pandanus utilis Bory	Pandanaceae	58	32	31.8	0.7658	0.8205
Pandanus vandermeeschii Balf.f.	Pandanaceae	68	31	30.3	3.8465	4.2920
Pandanus veitchii Mast.	Pandanaceae	72	33	32.2	2.1779	2.3984
Ravenala madagascariensis Sonn.	Strelitziaceae	85	31	30.6	1.0044	0.9468
Strelitzia alba (L.f.) Skeels	Strelitziaceae	51	32	31.1	3.5668	4.0547
Xanthorrhoea glauca D.J.Bedford	Xanthorrhoeaceae	78	31	31.5	1.4465	1.5779

Table A4. List of the Arecaceae species included in the carbon dioxide efflux study. Circ = circumference, Air T = air temperature, and Stem T = surface temperature of stems.

Species	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Adonia merrillii (Becc.) Becc.	66	33	31.9	1.4868	1.3255
Aiphanes minima (Gaertn.) Burret	53	33	31.8	3.3622	3.6797
Allagoptera caudescens (Mart.) Kuntze	52	32	30.8	1.6623	1.8051
Archontophoenix myolensis Dowe	87	31	32.8	2.4465	2.1460
Archontophoenix purpurea Hodel and Dowe	51	32	31.2	4.1657	3.6645
Areca catechu L.	59	32	31.8	1.8165	2.0134
Areca macrocarpa Becc.	61	33	32.1	3.7799	4.3046
Areca parens Becc.	59	33	33.9	3.2136	3.5649
Astrocaryum mexicanum Leibm. Ex Mart.	51	32	31.1	2.5644	2.2722
Beccariophoenix alfredii Rakotoarin., Ranariv. and J.Dransf.	182	33	32.9	1.1165	0.9864
Beccariophoenix madagascariensis Jum. and H.Perrier	103	32	31.2	3.6645	4.0031
Bentinckia nicobarica (Kurz.) Becc.	65	32	31.8	3.1619	3.4466
Borassodendron machadonis Becc.	127	33	31.2	2.8645	3.1165
Brassiophoenix schumannii (Becc.) Essig	52	33	32.1	1.7115	1.5274
Burretiokentia dumasii Pintaud and Hodel	51	32	31.1	2.7654	3.0031
Burretiokentia grandiflora Pintaud and Hodel	52	32	31.7	4.2958	4.7799
Burretiokentia vieillardii (Brongn. and Gris) Pic.Serm.	51	33	31.9	0.8286	0.8898

Table A4. *Cont.*

Species	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Calyptrocalyx spicatus (Lam.) Blume	52	34	32.9	1.2989	1.1361
Calyptronoma rivalis (O.F.Cook) L.H.Bailey	66	33	31.7	2.6798	2.9765
Carpentaria acuminata (H.Wendl. and Drude) Becc.	52	33	32.2	2.2722	1.7042
Carpoxylon macrospermum H.Wendl. and Drude	67	32	30.9	0.9346	0.9979
Caryota ophiopellis Dowe	81	32	31.1	3.9966	4.9643
Chambeyronia macrocarpa (Brongn.) Vieill. Ex Becc.	51	33	32.1	1.8879	1.6410
Chelyocarpus chuco (Mart.) H.E.Moore	51	32	31.1	3.6626	4.0033
Chelyocarpus ulei Dammer	51	33	31.8	4.7474	5.2646
Clinostigma ponapense (Becc.) H.E.Moore and Fosberg	62	33	32.1	3.6264	3.9986
Clinostigma samoense H.Wendl.	68	33	31.8	4.8946	5.3970
Cocos nucifera L.	105	32	31.4	3.7764	4.1133
Colpothrinax wrightii Griseb. and H.Wendl. ex Voss	101	33	32.2	1.8445	1.6474
Copernicia baileyana León	162	32	31.5	0.9631	0.9987
Copernicia hospita Mart.	61	31	30.3	3.0844	3.4125
Copernicia prunifera (Mill.) H.E.Moore	64	33	32.1	4.9497	5.4895
Copernicia sp. Mart. ex Endl.	68	32	31.6	1.3346	1.4653
Corypha utan Lam.	105	33	32.1	3.0888	3.4102
Cryosophila warscewiczii (H.Wendl.) Bartlett	61	33	31.9	4.0054	3.6103
Cryosophila williamsii P.H.Allen	52	32	31.1	5.4986	5.0896
Cyphophoenix elegans (Brongn. and Gris) H.Wendl. ex Salomon	51	33	32.1	2.7298	2.3755
Cyphophoenix nucele H.E.Moore	52	32	31.6	3.1959	3.0296
Cyrtostachys elegans Burret	58	32	31.1	4.1121	3.6570
Cyrtostachys loriae Becc.	52	33	32.1	3.1645	2.8165
Dictyosperma album (Bory) Scheff.	58	32	31.3	1.3896	1.2497
Dypsis arenarum (Jum.) Beentje and J.Dransf.	63	34	33.1	5.1132	4.5547
Dypsis cabadae (H.E.Moore) Beentje and J.Dransf.	52	33	32.7	3.3132	2.9765
Dypsis carlsmithii J.Dransf. and Marcus	77	33	32.9	4.6002	4.1165
Dypsis decaryi (Jum.) Beentje and J.Dransf.	81	32	31.2	3.4497	3.1133
Dypsis hovomantsina Beentje	62	33	33.7	1.3886	3.1349
Dypsis ifanadianae Beentje	58	33	33.1	4.1546	3.8845
Dypsis lastelliana (Baill.) Beentje and J.Dransf.	77	33	33.2	6.1132	5.6068
Dypsis madagascariensis (Becc.) Beentje and J.Dransf.	55	34	33.5	5.7746	5.1770
Dypsis mananjarensis (Jum. and H.Perrier) Beentje and J.Dransf.	65	34	31.9	3.8465	3.4545
Dypsis montana (Jum.) Beentje and J.Dransf.	65	33	32.2	4.0064	3.6699
Dypsis pembana (H.E.Moore) Beentje and J.Dransf.	68	29	28.1	4.5959	4.2236
Dypsis plumosa Hodel, J.Marcus and J.Dransf.	62	32	31.5	1.9976	2.8965
Dypsis robusta Hodel, Marcus and J.Dransf.	69	34	33.9	1.8465	1.6410
Dypsis saintelucei Beentje	55	34	33.1	1.9292	1.7042
Elaeis guineensis Jacq.	118	33	32.2	1.1645	1.0235
Euterpe precatoria Mart.	51	32	31.4	2.4265	2.1775
Heterospathe elata Scheff.	64	33	32.1	2.3164	2.1050
Heterospathe intermedia (Becc.) Fernando	51	32	31.2	4.3465	3.9133
Heterospathe sibuyanensis Becc.	74	34	31.9	2.0065	1.8304
Hydriastele moluccana (Becc.) W.J.Baker and Loo	84	34	33.1	3.8844	3.4466
Hyophorbe lagenicaulis (L.H.Bailey) H.E.Moore	151	31	30.4	2.8897	2.5878
Itaya amicorum H.E.Moore	55	32	30.9	2.4246	2.1460
Kentiopsis piersoniorum Pintaud and Hodel	55	33	32.1	1.4465	1.3255
Kentiopsis pyriformis Pintaud and Hodel	65	32	31.2	3.6611	3.2821
Laccospadix australasicus H.Wendl. and Drude	51	33	32.7	1.7996	1.5969
Licuala bayana Saw	51	32	30.8	2.1132	1.8935
Licuala peltata Roxb.	58	32	31.3	1.0054	0.8836
Licuala sallehana Saw	69	30	29.1	1.6632	1.5148
Livistona lanuginosa Rodd	97	33	32.1	2.8277	2.5247

Table A4. *Cont.*

Species	Circ (cm)	Air T	Stem T	Sample 1	Sample 2
Livistona mariae F.Muell.	88	33	32.3	1.1312	0.9957
Livistona muelleri F.M.Bailey	74	32	31.5	1.8486	1.6410
Livistona victoriae Rodd	79	31	30.9	1.6645	1.5148
Lodoicea maldivica (J.F.Gmel.) Pers.	98	34	34.6	1.1132	0.9720
Medemia argun (Mart.) Wurttenb. ex H.Wendl.	117	32	30.3	2.7918	2.5878
Neonicholsonia watsonii Drammer	52	32	30.8	1.7765	1.5148
Neoveitchia brunnea Dowe	55	33	31.8	2.0021	1.8051
Neoveitchia storckii (H.Wendl.) Becc.	73	32	31.2	1.2345	1.1109
Nephrosperma van-houtteanum (H.Wendl. ex Van Houtte) Balf.f.	52	33	32.3	2.7711	2.4657
Oenocarpus mapora H.Karst	51	32	31.1	5.5056	4.9231
Orania moluccana Becc.	68	29	28.6	1.6465	1.4391
Pelagodoxa henryana Becc.	67	32	31.3	1.4215	1.6410
Phoenix sylvestris (L.) Roxb.	109	31	32.9	3.7164	4.1132
Pinanga batanensis Becc.	68	34	32.9	3.6134	4.0066
Pinanga insignis Becc.	48	33	31.9	2.0311	1.8304
Pinanga javana Blume	51	34	32.8	2.1798	1.9566
Pinanga urosperma Becc.	61	33	31.9	0.9554	0.8205
Ponapea hosinoi Kaneh.	62	33	31.8	5.4165	6.0023
Prestoea acuminata (Willd.) H.E.Moore	52	32	30.8	4.0154	4.4651
Pritchardia thurstonii F.Muell. and Drude	66	29	28.6	0.7879	0.6943
Ptychosperma elegans (R.Br.) Blume	53	32	31.2	6.3897	7.1322
Ravenea madagascariensis Becc.	52	34	33.2	0.9498	1.1021
Rhopaloblaste augusta (Kurz.) H.E.Mllre	58	33	32.2	1.6355	1.4517
Rhopaloblaste ceramica (Miq.) Burret	72	32	31.1	1.6899	1.5148
Sabal mauritiiformis (H.Karst.) Griseb. and H.Wendl.	71	32	31.4	3.1134	3.2265
Sabal palmetto (Walter) Lodd. ex Schult. and Schult.f.	95	31	31.3	1.3444	1.2231
Saribus rotundifolius (Lam.) Blume	105	30	30.1	1.1314	1.0099
Satakentia liukiuensis (Hatus.) H.E.Moore	68	32	31.5	7.5109	6.3365
Schippia concolor Burret	51	33	32.4	0.7544	0.7547
Syagrus botryophora (Mart.) Mart.	76	32	32.6	1.7655	1.5779
Syagrus romanzoffiana (Cham.) Glassman	63	33	32.1	1.2615	1.1165
Syagrus sancona (Kunth.) H.Karst.	78	32	31.8	1.6311	1.4517
Syagrus schizophylla (Mart.) Glassman	56	32	31.1	1.5644	1.3886
Veitchia joannis H.Wendl.	59	33	32.2	1.3433	1.1992
Washingtonia robusta H.Wendl.	154	32	31.3	4.6899	4.2288
Wodyetia bifurcata A.K.Irvine	99	30	31.6	4.4454	3.9764

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