GUIDELINES FOR MONITORING CARBON SEQUESTRATION DURING FOREST RESTORATION

By Stephen Elliott

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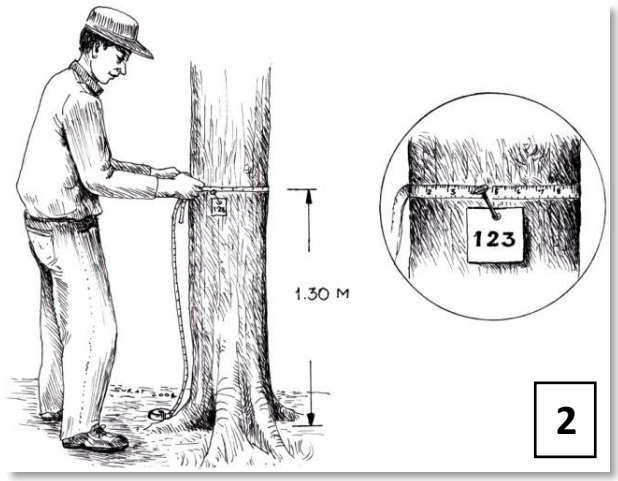
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INTRODUCTION

One of the main values of forest restoration is carbon storage. Growing trees remove carbon dioxide (CO_2) from the atmosphere—the main greenhouse gas responsible for global climate change. Trees absorb atmospheric CO_2 through pores (stomata) in their leaves and then chemically combine it with water by photosynthesis, powered by solar radiation, to produce sugar. Sugar is then biosynthesized, along with other elements, into a huge range of substances, including cellulose and lignin, which make up wood. Most of the carbon absorbed by forests ends up in tree trunks, and eventually in the soil, as trees drop leaf litter and dead branches etc. and eventually die.

In countries with cap-and-trade systems, legislated to meet commitments under global agreements on climate change, industries that emit CO_2 must either reduce CO_2-emitting processes or replace them with non-CO_2 emitting ones. If they cannot do these things, then they must pay for CO_2 to be removed from the atmosphere, by buying carbon credits. In northern Thailand, the carbon-credit value of forest restoration could amount to about 16x times the value of alternative land uses, such as maize cultivation, if the government legislates a cap-and-trade system and creates the necessary market mechanisms (Jantawong et al., 2022). Consequently, future rural livelihoods could depend on the accurate measurement of how much carbon is absorbed by forest restoration.

AIMS

1. To provide students with experience of working field measurement protocols to determine carbon accumulation rates during forest restoration.
2. To enable students to understand and perform the calculations needed to convert field data in carbon-storage estimates and understand the limitations of such calculations.

EQUIPMENT AND MATERIALS

Trees: metal labels (made from drinks cans), permanent marker, metal stylus, wire, nails, tape measures (1.5 m), data sheets, pencils, clip boards, tree height measuring poles and digital clinometer.
Herbaceous vegetation: shears, scissors, 1 x 1 m wire quadrat, large paper bags or newspaper and stapler, oven, portable electronic balance.
Soil: soil corer 5 cm diameter, marker pens, large zip-lock bags, trowel, drying room, drying oven, battery operated portable electronic balance (to 0.01 g).

Opposite - Figure 1 – Example photo monitoring.
Figure 2 – Place upper edge of label 1.3 m above ground and measure GBH (cm) there with tape measure.
Figure 3 – Sample soil with a core sampler 5 cm diameter and 15 cm deep
Figure 4 – Measures tree height with telescopic measuring pole or with digital clinometer (cover).

METHODS

When to monitor carbon

Collect data just before and after forest restoration interventions are initiated (baseline) and annually thereafter, at least until regeneration is well underway. The best time to perform monitoring is at the end of each rainy season.

Where to monitor carbon

To assess if forest restoration increases carbon sequestration above that which would occur natural, three sites must be surveyed:

i) restoration plots (treatment)
ii) control plots (origin, where natural regeneration proceeds unassisted) and
iii) reference forest plots (target).

Comparing i) and ii) determines the effectiveness of FSM interventions above what could be achieved solely by natural regeneration, whilst comparing i) and iii) tracks the progress of restoration towards the ideal end-state.

Establish a minimum of 8 circular sample units (SUs) in each of the 3 sites (randomly placed). Mark the centre of each circle with a labelled metal pole. Record the details of each SU on Data Sheet 1.

Procedures in each SU

Photo monitoring

At each SU centre pole, take 4 photos, looking out from the pole roughly N, E, S and W (in that order). Set the camera to the widest possible zoom setting and the highest resolution. Frame each picture to include the top of the pole (showing the pole i.d. number) in the lower right-hand corner. Use a compass to record the direction of the photo. Keeping the top of the pole in the lower right-hand corner of the picture, gradually tilt the camera down to minimized the amount of sky in the shot, so the horizon should be near the top edge of the picture. Repeat photo-monitoring in the mid dry and wet seasons and at annual intervals. Use the same camera with the same zoom and resolution settings for all photos. Transfer photos to a computer as soon as possible and rename the files as follows: pole reference number_date (yymmdd) e.g., MC22_01_220901 (Mon Cham 2022 plot, SU #1, photo 1st Sept. 2022).

Measuring trees

Use a piece of string 5 m long to count and label all trees with girth at breast height (GBH) of >5.0 cm, within 5-m distance of the centre pole at each SU. Nail labels to the trunk, so that the upper edge of the label is at exactly 1.3 m above the ground, where GBH will be measured. Use 5 cm long, galvanized nails, with flat heads. Hammer only about 1/3 of the nail length into the trunk to allow plenty of room for tree growth. On datasheet 2, record i) the label number,

ii) the species name (both local name and scientific name), iii) GBH (use 1.5-m tape), iv) height (by measuring pole or digital clinometer), v) crown length and width.

Herbaceous vegetation mass

Directly north of the centre pole crop exactly 1 sq m of the ground vegetation with a pair of shears, as close as possible to the soil surface. Weigh an empty paper bag with a portable electronic balance to the nearest gram. Place the vegetation sample into the bag and weigh again. Derive the wet sample weight by subtracting the bag weight. Label the bag. In the lab, dry the samples in an oven, overnight at 80°C. Make sure no material is lost during the transfer and drying process. Then reweigh the samples. Use Data Sheet 3 to calculate the dry mass of herbaceous vegetation (in g/m^2). At subsequent monitoring events, clip vegetation west, south and east of the pole etc.

Soil

Push a soil corer **of 5 cm in diameter**[1] into the soil to a depth of **exactly** 15 cm and gently withdraw the corer, keeping the soil column intact. Reject any cores with thick roots, large stones or with soil missing from parts of the core. Place each sample into a separate plastic bag and label each bag with SU identification number and date etc. with an indelible marker. Use a portable electronic balance in the field, to measure the wet mass of each sample (subtract the weight of the plastic bag). The top 15 cm of soil usually accounts for 20-40 % of the carbon in the whole soil profile.

In the lab, determine the dry mass of soil particles in the whole soil core (0-15 cm) by first placing each sample into a pre-weighed aluminium foil tray and air drying each sample. Separate roots and stones from each dry sample with a 2-mm-mesh sieve. Then return all sieved material to the aluminium foil tray and continue to dry at 105°C for a further 24 h. Check if the soil is completely dry by drying it for a further 12 h and recording no further weight loss. Weigh the completely dry soil with an electronic balance and enter the value into Data Sheet 4. Thoroughly mix the dry material from each core sample and take a sub-sample of around 500 gm of each dry core material. Send the samples to CMU Agriculture Soil Lab for carbon content analysis by the Walkley-Black technique (Nelson and Sommers 1982, Walinga et al. 1992). Enter the % carbon content into Data Sheet 4.

DATA ANALYSIS

Transcribe your data into this spreadsheet to perform data analysis. The spreadsheet has separate tabs to calculate carbon in trees, herbaceous vegetation and soil and for totaling carbon in all three pools for each SU. For carbon accounting, all measurements (trees, herbaceous vegetation and soil) must be converted into the same units i.e., metric tonnes of carbon per hectare. 1 hectare = 10,000 m^2 or 100,000,000 cm^2. 1 metric tonne = 1,000 kg or 1,000,000 gm.

[1] The diameter of the soil core and the depth of the soil core are critical to carbon calculations. **They must be known exactly.**

Trees

Allometric equations predict a difficult-to-measure parameter (i.e., tree dry biomass) from an easily measured one (i.e., DBH). They are originally constructed by felling trees of different sizes and then drying and weighing the whole tree. A graph is plotted of dry mass vs a function of DBH, height and wood density. The equation, derived from the shape of the curve, can subsequently be used to predict tree dry mass from field measurements, without the need for any further destructive sampling. Titinan Pothong (Pothong et al., 2022) determined the best equation for trees in regenerating forest in northern Thailand is …

$$\mathbf{AGB} = \boldsymbol{a}\ \boldsymbol{x}\ (\mathbf{D}^2 \times \mathbf{H} \times \mathbf{WD})^{\boldsymbol{b}}$$

… where **AGB** means above-ground dry biomass (**kg**); **D** = diameter at breast height (**cm**); **H** = tree height (**m**) and **WD** = wood density **(g/cm^3)**. The parameters **"a"** and **"b"** are constants, derived from Pothong's field data of felled trees. Recommended values for northern Thailand trees are **0.134 and 0.847** respectively, for trees of D 1 to 20 cm and **0.0673 and 0.976** for trees of D > 20 cm.

Set up a spreadsheet, one line per tree, with columns for GBH, DBH, tree height and WD. Enter GBH and height values from Data Sheet 1. Calculate the diameter at breast height D (cm) by dividing GBH by pie π (3.14159) and square it. In the WD column, copy the value 0.52 (g/cm^3) down all lines. This is the mean wood density across all species in Pothong's study of trees regenerating on fallow fields in northern Thailand. You could make your spreadsheet more accurate by looking up the wood density of individual tree species and overwriting "0.52" with species-specific values listed in Appendix 1. If you cannot find species there, try the online global wood density database:

http://db.worldagroforestry.org/wd

Create a box at the top of the spreadsheet to store values of parameters: "a" and "b". Next, insert a column, to solve the above equation and return a value for predicted dry AGB for each tree. Adjust the solution to include root dry biomass. For tropical trees, Cairns et al. (1997) determined a mean root/shoot ratio on 0.24 tons roots per ton AGB. Therefore, multiply the above-ground tree dry biomass by 1.24, to derive ***total*** tree dry biomass (kg). Pothong reported that average carbon content of the trees in her study was 44.84% of dry biomass. So, multiply the result by 0.4484 to convert ABG to above ground carbon (ABC).

Sum the values for all trees in each SU (kg/circle) and convert to metric tonnes per ha. You end up with one estimate of carbon quantity (metric tonnes per ha) for each circle.

Herbaceous vegetation

Multiply dry biomass of herbaceous vegetation sampled from 1 m^2 by 1.35, to add estimated root mass, and then by 0.44, to convert biomass to carbon (g/m^2). Then, multiply the result by 10,000 to extrapolate the estimate to 1 ha and then divide the result by 1,000,000,000 to convert g/ha to ton/ha.

Top Soil

For top soil, the measurements obtained are total mass (g) dry soil in a core 15 cm long x 5 cm diameter and the per cent carbon content from the lab analysis. The carbon in the sample is determined by multiplying the sample dry mass by the per cent carbon content/100 result from lab analysis. The derived mass of carbon is divided by the cross-sectional area of the core to get a value of carbon "per cm^2". The result is multiplied by 100,000,000 to get a value "per ha" and divided by 1,000,000 to convert grams to metric tonnes.

$$\text{Soil tC/ha} = \frac{\text{Core dry mass x (\% carbon content/100)}}{(3.14159 \times (\text{core radius (cm)})^2)} \times \frac{100{,}000{,}000}{1{,}000{,}000}$$

Finally, sum carbon in trees, herbaceous vegetation and top soil in tons/h for each SU and calculate the mean values and 95% confidence limits for control, restoration and reference forest sites and perform ANOVA and t-tests to determine if differences are significant. Also look for differences in the relative per centages of carbon in each of the three pools among the three sites.

Can you find a way to put a monetary value on carbon storage during forest restoration? How might such value compare with alternative land uses ((Jantawong et al., 2022)?

In your discussion, evaluate the pros and cons of both field work methods and subsequent calculations. What further research is needed to improve the precision and accuracy of carbon measurements during forest restoration.

This small collection of research papers, from CMU students researching carbon storage during forest restoration in northern Thailand might help you with your report:

https://www.forru.org/library?t%5B0%5D=38

Citations and Further Reading

Jantawong, K.; Kavinchan, N.; Wangpakapattanawong, P.; Elliott, S. Financial Analysis of Potential Carbon Value over 14 Years of Forest Restoration by the Framework Species Method. *Forests* **2022**, *13*, 144. https://doi.org/10.3390/f13020144 https://www.forru.org/library/0000228

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Data Sheet 1 - Sample Unit (SU) Details

SAMPLE UNIT DETAILS		
		Sample Unit I.D. #:
Diameter (m):		CONT / RESTN / REF FOR
Slope:	Aspect:	Elevation:
GPS:	N	E
Signs of Fire:		
Signs of livestock impact:		
Signs of erosion:		
Distinguishing features:		
Photos	Compass direction (degrees)	Photo File I.D. #
N		
E		
S		
W		

Data Sheet 2 – Tree Size

LOCATION					DATE:
SAMPLE UNIT ID #:		RECORDER:		CONT / RESTN / REF FOR	
Within 5-m radius circle - count tree of GBH >5 cm only					
Label	Tree Species	GBH (cm)	Height (m)	Crown Length (m)	Crown Width (m)	Notes
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					
	Local Sci.					

Data Sheet 3 – Herbaceous Vegetation Mass

	Field			Lab			
SU	Weight PAPER bag (field) (g)	Wet sample + bag (g)	Wet sample weight (g/sq m)	Weight paper bag (lab) (g)	Dry sample + bag (g)	Dry sample weight (g/sq m)	% Water content

Data Sheet 4 – Soil Samples for Carbon Content Analysis

CORE RADIUS……SAMPLE DEPTH ……

LOCATION				DATE:				
RECORDER:								
	WEIGHTS (g)							
	Field			Lab				
SU#	Bag (g)	Wet sample + bag (g)	Wet sample (g)	Foil tray (g)	Wet sample + foil tray (g)	Dry sample + foil tray (g)	Dry biomass sample (g/sq m)	% Water content

Appendix 1 - Species-specific Wood Density Data for Northern Thailand Trees

Supplementary data from Pothong et al. (2021) https://www.forru.org/library/0000230

Supplementary table S5

Average wood density (WD) of tree species in this study, Global Wood Density (GWD) and Genus from Zanne et al. (2009), "No." refers to the species ID number.

No.	Species name	WD (g cm^{-3}) (This study)			GWD (g cm^{-3})			Genus (g cm^{-3})		
		$\bar{x}$±SD	n	min-max	$\bar{x}$±SD	n	min-max	$\bar{x}$±SD	n	min-max
1	*Actinodaphne henryi*							0.51±0.09	8	0.4-0.65
2	*Adenanthera microsperma*				0.64	1				
3	*Albizia chinensis*	0.4±0.07	9	0.26-0.49	0.30	1				
4	*Albizia lebbeck*				0.6±0.12	6	0.45-0.8			
5	*Albizia odoratissima*	0.63	1		0.64±0.06	6	0.57-0.71			
6	*Alstonia rostrata*	0.37±0	2	0.36-0.37						
7	*Anneslea fragrans*	0.58±0.07	2	0.53-0.63	0.68±0.05	3	0.63-0.72			
8	*Anogeissus acuminata*				0.88	1				
9	*Antidesma acidum*							0.65±0.08	13	0.51-0.8
10	*Antidesma sootepensis*	0.53±0.07	4	0.47-0.62						
11	*Aporosa octandra*	0.58±0.01	2	0.57-0.58						
12	*Aporosa villosa*	0.51±0.08	70	0.46-0.54						
13	*Archidendron clypearia*	0.41±0.04	8	0.34-0.47	0.32±0.06	3	0.26-0.37			
14	*Artocarpus lacucha*							0.48±0.1	63	0.27-0.73
15	*Berrya mollis*	0.44±0.03	4	0.39-0.46						
16	*Bombax anceps*	0.19±0.01	2	0.19-0.2	0.41	1				
17	*Buchanania lanzan*	0.47±0.07	3	0.42-0.56	0.39±0.09	2	0.33-0.45			
18	*Callicarpa arborea*	0.44	1							
19	*Calophyllum inophyllum*	0.34	1		0.58±0.04	5	0.53-0.64			
20	*Canarium subulatum*	0.41±0.08	38	0.2-0.52						
21	*Canthium glabrum*	0.54±0.05	11	0.47-0.63	0.41	1				
22	*Castanopsis acuminatissima*	0.59±0.11	26	0.42-0.76	0.58±0.01	2	0.58-0.59			
23	*Castanopsis calathiformis*	0.67±0.03	2	0.65-0.69						
24	*Castanopsis diversifolia*	0.57±0.09	35	0.35-0.78						
25	*Castanopsis lucida*	0.51±0.03	6	0.46-0.54	0.53	1				
26	*Castanopsis tribuloides*	0.6±0.07	30	0.48-0.77	0.59±0.12	2	0.51-0.68			
27	*Celtis tetrandra*	0.58±0.05	2	0.55-0.62	0.52	1				
28	*Cinnamomum camphora*				0.49±0.08	5	0.42-0.62			
29	*Cinnamomum verum*				0.50	1				
30	*Colona winitii*	0.44	1							
31	*Craibiodendron stellatum*	0.62±0.05	3	0.56-0.67						
32	*Cratoxylum cochinchinense*				0.67±0.1	2	0.6-0.74			
33	*Cratoxylum formosum*	0.62±0.02	3	0.6-0.64	0.72±0.06	4	0.64-0.76			
34	*Dalbergia cana*	0.62±0.08	2	0.57-0.68						
35	*Dalbergia cultrata*	0.53±0.05	32	0.43-0.67	0.77	1				
36	*Dalbergia oliveri*	0.46±0.03	2	0.44-0.48	0.88±0.04	2	0.85-0.91			
37	*Dalbergia ovata**				0.68	1				
38	*Dillenia parviflora*	0.6±0.06	5	0.53-0.68	0.56	1				
39	*Dimocarpus longan*				0.70	1				
40	*Diospyros glandulosa*	0.51±0.06	2	0.47-0.55						
41	*Dodonaea viscosa*				0.95±0.15	2	0.84-1.05			
42	*Elaeocarpus stipularis*	0.64	1		0.45±0.02	2	0.43-0.46			
43	*Engelhardtia serrata*				0.37	1				

No.	Species name	WD (g cm^{-3}) (This study)			GWD (g cm^{-3})			Genus (g cm^{-3})		
		x̄±SD	n	min-max	x̄±SD	n	min-max	x̄±SD	n	min-max
44	*Engelhardtia spicata*				0.44±0.06	3	0.37-0.49			
45	*Eriolaena candollei*				0.70	1				
46	*Erythrina subumbrans*	0.32	1		0.23	1				
47	*Eugenia albiflora*							0.73±0.12	95	0.49-1.3
48	*Eugenia cumini*	0.57±0.05	3	0.52-0.61	0.56	1				
49	*Eugenia fruticosa*	0.49±0.09	31	0.34-0.71						
50	*Eurya acuminata*	0.56±0.06	6	0.47-0.62	0.50	1				
51	*Fernandoa adenophylla*	0.63±0.04	2	0.61-0.66	0.49	1				
52	*Ficus fistulosa*	0.24±0.05	9	0.14-0.31	0.38	1				
53	*Ficus hirta*							0.41±0.09	153	0.14-0.68
54	*Ficus hispida*				0.38±0.04	2	0.35-0.41			
55	*Ficus semicordata*	0.36±0.08	8	0.25-0.5						
56	*Flacourtia indica*	0.67±0.03	4	0.65-0.71	0.74±0.07	2	0.69-0.78			
57	*Garcinia cowa*				0.55	1				
58	*Garcinia xanthochymus*				0.79	1				
59	*Gardenia sootepensis*							0.67±0.07	14	0.56-0.77
60	*Glochidion rubrum*				0.64	1				
61	*Glochidion sphaerogynum*	0.46	1							
62	*Gluta usitata*	0.64	1		0.74	1				
63	*Grewia eriocarpa*	0.47±0.01	2	0.46-0.49	0.67	1				
64	*Helicia nilagirica*	0.53±0.07	36	0.42-0.76	0.64±0.02	3	0.62-0.66			
65	*Heynea trijuga*	0.53±0.07	2	0.48-0.57	0.45	2	0.45-0.55			
66	*Ilex umbellulata*	0.44±0.06	24	0.28-0.54						
67	*Ixora cibdela*							0.79±0.1	7	0.69-0.96
68	*Knema cinerea*							0.53±0.05	19	0.44-0.63
69	*Lagerstroemia tomentosa*				0.54	1				
70	*Lepisanthes tetraphylla**				0.81±0.21	2	0.66-0.96			
71	*Lindera meisneri*							0.52±0.1	8	0.36-0.64
72	*Lithocarpus garrettianus*							0.67±0.12	65	0.44-0.88
73	*Lithocarpus polystachyus*	0.65±0.11	119	0.41-1.03						
74	*Litsea glutinosa*	0.29	1		0.5±0.08	2	0.44-0.56			
75	*Litsea lancifolia*	0.43	1							
76	*Litsea monopetala*	0.44	1		0.42±0.03	6	0.38-0.45			
77	*Macaranga denticulata*				0.43±0.07	4	0.33-0.49			
78	*Macaranga kurzii*							0.38±0.12	57	0.23-0.7
79	*Magnolia baillonii*	0.42±0.04	2	0.39-0.45						
80	*Magnolia hodgsonii*	0.51±0.15	3	0.41-0.69	0.62	1				
81	*Mallotus philippensis*							0.5±0.12	29	0.32-0.7
82	*Mangifera indica*				0.55±0.07	6	0.48-0.68			
83	*Markhamia stipulata*	0.44±0.06	2	0.4-0.48	0.68±0.18	2	0.55-0.8			
84	*Meliosma simplicifolia*				0.45	1				
85	*Memecylon scutellatum*	0.41	1							
86	*Muntingia calabura*				0.30	1				
87	*Olea rosea Craib*	0.59±0.11	4	0.45-0.68						
88	*Oroxylum indicum*	0.32	1		0.41±0.07	3	0.34-0.48			
89	*Phoebe lanceolata*	0.52±0.09	24	0.4-0.78	0.69	1				
90	*Phyllanthus emblica*	0.5±0.07	72	0.35-0.72	0.64±0.06	3	0.57-0.68			
91	*Polyalthia cerasoides*	0.56±0.09	4	0.43-0.63	0.76±0.11	2	0.68-0.83			
92	*Polyalthia viridis*	0.49±0.03	3	0.45-0.52						
93	*Protium serratum*	0.43	1							
94	*Pterocarpus macrocarpus*				0.70	1				
95	*Quercus kerrii*	0.68	1							
96	*Quercus kingiana*	0.58±0.09	50	0.29-0.78						
97	*Quercus semiserrata*	0.63±0.05	9	0.55-0.73	0.71±0.05	3	0.66-0.76			
98	*Rapanea yunnanensis*	0.59±0.05	3	0.53-0.63						
99	*Rhus chinensis*							0.59±0.21	14	0.37-1.01
100	*Sapindus rarak*	0.48±0.04	8	0.43-0.55	0.51	1				

No.	Species name	WD (g cm^{-3}) (This study)			GWD (g cm^{-3})			Genus (g cm^{-3})		
		x̄±SD	n	min-max	x̄±SD	n	min-max	x̄±SD	n	min-max
101	*Sarcosperma arboreum*	0.54±0.02	2	0.53-0.56	0.46	1				
102	*Schima wallichii*	0.53±0.06	47	0.39-0.72	0.56±0.04	8	0.5-0.62			
103	*Schoepfia fragrans*	0.57	1							
104	*Semecarpus albescens*	0.54±0.03	4	0.5-0.58	0.26	1				
105	*Shorea roxburghii*	0.64±0.05	3	0.61-0.71	0.70	1				
106	*Spondias lakonensis*	0.29	1							
107	*Spondias pinnata*	0.34	1		0.29±0.06	5	0.22-0.36			
108	*Sterculia balanghas*							0.43±0.13	79	0.2-0.7
109	*Stereospermum colais*	0.45±0.05	3	0.4-0.49						
110	*Stereospermum neuranthum*	0.61±0.06	3	0.54-0.66						
111	*Styrax benzoides*	0.58±0.07	33	0.35-0.8	0.00	1				
112	*Symplocos macrophylla*	0.53	1							
113	*Toona ciliata*	0.49	1		0.38±0.04	6	0.33-0.43			
114	*Turpinia pomifera*	0.49±0.04	5	0.45-0.56						
115	*Vitex limonifolia*							0.55±0.12	41	0.4-0.9
116	*Wendlandia tinctoria*	0.55±0.09	27	0.37-0.73						
117	*Xanthophyllum virens*	0.54	1							
	Average	**0.51±0.11**	**883**	**0.14-1.03**	**0.56±0.15**	**142**	**0.22-0.88**			

*Trees of these species died before sample collection