NOTE / NOTE

Growth assessment in tropical trees: large daily diameter fluctuations and their concealment by dendrometer bands

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Abstract: Tree stems contract and expand as stem water is depleted and replaced. Band-dendrometer studies suggest that such daily changes are small (<0.2 mm diameter), and they are ignored in most growth measurements. However, several studies using other approaches note larger changes (even >1 cm diameter), suggesting that significant biases are possible. An exploratory study examined the pattern and magnitude of daily stem changes and whether commercial band-dendrometers were able to reveal them. A method involving multiple precision measurements on eight trees in a Bornean hill dipterocarp forest revealed daily shrinkage and expansion of girth of around 1 mm. Fluctuations were greater in bright weather. Band-dendrometers detected these changes but revealed less than a tenth of their magnitude. An analytical model for dendrometer error is presented that predicts how measurement biases can be reduced. Tropical trees can fluctuate appreciably in stem diameter over the day. These reversible changes are of sufficient magnitude to merit concern in growth studies. Influential biases seem especially likely when measurement intervals are short and involve systematic differences in timing and weather. Further study is required to gauge the more general influence of these measurement problems.

Résumé : La tige des arbres se contracte ou se dilate lorsque l'eau dans la tige s'épuise ou est remplacée. Des études avec des dendromètres à ruban suggèrent que de tels changements journaliers sont faibles (inférieurs à 0,2 mm de diamètre) et ils sont ignorés dans la plupart des mesures de croissance. Cependant, plusieurs études utilisant d'autres approches notent de larges changements (même supérieurs à 1 cm de diamètre) suggérant que des biais significatifs sont possibles. Une étude exploratoire a examiné le patron et l'amplitude des changements journaliers de la tige et la capacité des dendromètres à ruban commerciaux à détecter ces changements. Une méthode impliquant plusieurs mesures de précision sur huit arbres dans une forêt de montagne à diptérocarpacées de Bornéo, a révélé des rétrécissements et dilatations journaliers d'environ 1 mm en circonférence. Les fluctuations étaient plus importantes par temps clair. Les dendromètres à ruban ont détecté ces changements, mais avec moins du dixième de son amplitude. Un modèle analytique de l'erreur due au dendromètre qui permet de réduire le biais des mesures, est présenté. Le diamètre de la tige des arbres tropicaux peut fluctuer de façon appréciable au cours d'une journée. Ces changements réversibles ont une amplitude suffisante pour être pris en compte dans les études de croissance. Des biais appréciables semblent se produire particulièrement lorsque les intervalles de mesure sont courts et impliquent des différences systématiques dans la température et le moment où les mesures sont prises. D'autres études sont nécessaires pour quantifier l'influence plus générale de ces problèmes de mesure.

[Traduit par la Rédaction]

Introduction

Tree growth estimates derived from measured stem changes are used in many aspects of forest science. However, not all changes reflect woody growth (Sheil 1995; Clark et al. 2001). It has long been known that reversible tree stem shrinkage can be substantial (Karling 1934; Haasis 1934; Fielding and Millett 1941; Daubenmire 1972). The physiological explanation is that trees possess a reservoir of water in their stems (e.g., Borchert 1994; Holbrook 1995; Goldstein et al. 1998; Stratton et al. 2000) and transpiration induces reversible stem constriction through reduction in xylem pressure (Kozlowski et al. 1991). Temperate studies sometimes show substantial size changes over short periods of time (e.g., Haasis 1934; Fielding and Millett 1941; Stephens and Spurr 1948; Bay 1963; Kozlowski and Winget 1964; Kozlowski 1965, 1972; Zahner 1968; Kozlowski et al. 1991; Downes et al. 1999). However, in tropical trees,

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where transpiration demands may be greater, the subject is little studied.

This paper investigates tropical tree stem diameter fluctuations and reviews past studies. Using observations from Indonesian Borneo, it shows that significant diurnal changes do occur and that band-dendrometers, the "standard" for recording short-term changes, can underestimate their magnitude. The potential to cause bias in forest growth monitoring is discussed. A model to predict dendrometer error and to suggest improvements is provided.

Previous evidence

I previously suggested that reversible flexing might explain some long-term growth patterns from a semideciduous Ugandan forest (Sheil 1997). Stem populations from five plots of over 1.8 ha each varied significantly in growth over consecutive multiyear intervals. In general, the very slowest growing stems grew faster over wetter measurement periods, while most stems grew slower. In Uganda, wet season measures often take place in bright conditions (cloud generally builds up later in the day) when the trees are in full leaf and transpiration demands are high.

How large are reported daily changes in tropical trees? Unfortunately, information is scarce. CABI's compendium of forestry research abstracts (1939–2001) yields only two studies (Iyamabo 1971; Yoda and Sato 1975), both of which are incompletely reported. These and six other studies are described in Table 1. In summary, two band studies (Sumatra and Ghana) imply small daily fluctuations (0–0.1 mm in diameter), while five using other methods (Uganda, Malaysia, Honduras, Uruguay, and Java) found bigger changes (0.5 mm to >10 mm). One study (Nigeria) found clear daily patterns but their magnitude was not reported.

Suitable data to estimate stem changes in relation to water use are hard to find. Andrade et al. (1998) and Goldstein et al. (1998) detailed whole-tree water use for one 35-m-tall, 1.02-m-diameter *Anacardium excelsum* in Panama. They reported that "the amount of water withdrawn from stem storage and subsequently replaced daily is 54 kg" (Goldstein et al. 1998). Considering this deficit against stem volume implies a volumetric ratio of around 0.4%. If reflected in daily diameter changes, this implies shrinkage of around 2 mm. Given rigid vessels, this value is an upper estimate, but millimetre-scale changes appear to be plausible.

To clarify both the magnitude of daily changes and whether band methods can reveal them, a small exploratory study was undertaken.

Methods

Site and tree selection

The site is the Centre for International Forestry Research's (CIFOR) field camp in Malinau, East Kalimantan (Borneo), Indonesia (UTM50, 44°55′00″E, 33°23′00″N). Annual rainfall is between 3000 and 4000 mm. Vegetation is evergreen lowland dipterocarp forest. Eight trees were subjectively selected for their wide undistorted boles (Table 2). All lie within 50 m of each other, 20–50 m from the flood-prone Seturan River, about 100 m above sea level, on level alluvial sandy clay soils.

Measurement procedures

Dawkins' (1956) multiple-measures (DMM) approach

Each bole was scrubbed clean. Eight separate measurement paths were marked at 10-cm intervals above any buttresses. For each path, three near-equidistant points were aligned using a straight edge and marked with oil-based paint. During measurement, a steel tape was aligned to the points (requiring two people) and girth recorded to the nearest millimetre. Ladders were needed on each side of some stems. For analyses, the eight records were averaged to provide per stem means.

Band-dendrometers

Band-dendrometers (Series 5, high tension, from Forestry Suppliers Inc., Jackson, Miss.) were installed on four stems above any buttresses and between the DMM markings. The scale housing is bolted to the tree and holds one end of the metal band fixed. The other end is attached to a constant-tension spring (1.22 N) and adjustable vernier scale providing 0.1-mm resolution. One band was subsequently damaged. Recording commenced 10 days after installments. "Training readings" (not used) had confirmed that all units were showing change.

Schedule

Two circuits were completed each day: 0700 to 0800 hours and 1500 to 1600 hours. Each circuit took approximately 1 h. DMM and dendrometer readings were taken together.

Weather

Each day, hourly classifications of weather were made and weighted to provide a rough index of transpiration demand. The classes (and weights) were as follows: S, full sun (10); CL, clear (6); LC, light cloud (4); OC, overcast (2); R, rain (–10). Overnight rain, although recorded, is not included in the index because, given the wet weather encountered, soils were never dry and moisture was not considered a limiting factor.

Results

The dendrometer, DMM, and weather data are presented, aligned by days, in Fig. 1. The dendrometers show only small size changes during the measurement period. A minuscule (<0.1 mm) diurnal rhythm in girth is detected in two of the three stems (Table 3).

The DMM method shows clear daily girth shrinkage of all eight stems of about 1 mm, or 0.1%–0.2% of stem size. Changes of over 2 mm were occasionally recorded (Table 3). The DMM fluctuations are statistically significant and highly correlated: all of the 28 possible stem pairings have positive rank correlations, and all but two have P values below 0.05 (20 having $P = 0.001$). Comparing dendrometer and DMM measures for these stems yields positive rank correlations (tree B, $\tau = 0.57$, $P < 0.001$; tree C, $\tau = 0.195$, $P = 0.23$; tree D, $\tau = 0.333$, $P = 0.032$; all $n = 24$).

The daily magnitudes of change are the differences between morning and afternoon girths (i.e., a positive difference denotes shrinkage). Summary statistics are provided in Table 3. The DMM series daily magnitudes are synchronized (26 of 28 pairings are positively correlated, 12 with $P <$

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Table 1. Tropical studies recording diurnal tree stem diameter changes.

Location	Population	Method	Results	Source
Pasoh, Malayasia	26 stems over 7 cm in diameter in a 10 m × 20 m plot	33 plate-gauge (not band) dendrometers. Radial changes were recorded hourly over 2.5 days	All trees showed a daily cycle with largest sizes generally achieved at night or early morning and minimum size in midafternoon. Unfortunately, stem sizes are only provided for four individuals. Summary implies that approximately 0.5–1 mm daily changes in girth are normal (even on the smallest stems)	Yoda and Sato 1975
Kibale, Uganda	Eight large stems for 10 days	Dawkins' (1956) method of multiple measures (see main text) was used	Despite dull overcast weather, daily changes of approximately 0.2% of stem size and a longer term shrinking trend were detected in all of the trees	K. Affum-Baffoe et al., unpublished; Sheil 1997
Tinte Bepo and Bonsa River, Ghana	42 *Celtis mildbraedii* in a semideciduous forest	Dendrometer bands (liming type). Four occasions twice a day: 0800 to 1200 hours and 1600 to 1800 hours	Combining results for all four occasions, mean ± SE diurnal diameter change was 0.017 ± 0.015 mm (n = 59), i.e., a small change but not significantly different from zero	Baker et al. 2003
Jambi, Sumatra, Indonesia	Five planted rubber trees (*Hevea brasiliensis*), 60–90 cm in girth, in "near-open" conditions	Dendrometer bands (liming type). 0600 and 1800 hours over a period of 8 days	Two of the five trees showed some degree of daily shrinkage, but the mean daily girth change remained less than the minimum measurement unit of 0.1 mm	G. Vincent et al., unpublished
Honduras	Sapodilla (*Achras zapota*) trees	The exact technique is not described but a detailed series of continuous readings are presented	Implies daily changes in diameter of 5 mm or more (in stems about 30 cm in diameter). Results show that daily changes are less when soil moisture is limited, and large changes occur in bright but wet conditions	Karling 1934
Uruguay	Unclear	Unclear	Reported as "similar" to Karling (1934) (above)	Hall 1890, cited in Karling 1934
Bogor, Java, Indonesia	"Many different types"	"Measured at different time intervals of the day"	"The trees usually decreased in diameter during the forenoon and early afternoon and begin to increase at approximately 3:00 pm, thus showing daily reversible variation. *Oreodoxa regia*, for instance, varied as much as 1.02 cm over a period of seven hours"	Kraus 1895, cited in Karling 1934
Nigeria	"Three small *Triplochiton scleroxlon* [sic] H. Schum"	Not stated	Clear daily changes noted (but magnitude not given) (see figs. 2*a* and 2*b* in Iyamabo 1971)	Iyamabo 1971

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Table 2. Trees used in the diameter change assessment conducted for this study.

Tree	Species	Dendrometer bands	Crown position*	Crown form*	Estimated height (m)	Buttressing to (m)	Height of lowest reading (m)	Girth (cm)	Diameter (cm)
A	*Gironnera subaquilis* Planch. Ulmaceae	No (broken)	3	5	16	None	1.1	76.2	24.3
B	*Litsea garciae* Vidal Lauraceae	Yes at 1.5 m	5	5	18	0.5	1.2	174.2	55.5
C	*Mallotus* c.f. *muticus* (M.A.) Airy Shaw Euphorbiaceae	Yes at 1.8 m	4	3	23	1.2	1.5	151.4	48.2
D	*Mallotus* c.f. *muticus* (M.A.) Airy Shaw Euphorbiaceae	Yes at 1.5 m	3	2	20	0.7	1.2	124.9	39.8
E	*Aglaia* c.f. *argentea* Bl. Meliaceae	No	3	2	18	0.6	1.3	87.5	27.8
F	*Litsea garciae* Vidal Lauraceae	No	4	4	20	1.6	1.8	160.8	51.2
G	*Dryobalanops lanceolata* Burck Dipterocarpaceae	No	5	3	36	1.8	2	179.4	57.1
H	*Bhesa paniculata* Am. Celastraceae	No	3	2	26	2	2.2	161.0	51.2

*Crown classes as per Dawkins (1958).

0.1, $n = 12$). Figure 1 suggests that fluctuations during wetter periods are reduced with the larger fluctuations in intervening bright periods. All DMM series daily magnitudes showed a positive relationship to the daily weather index (12 of 12 positive, $P = 0.00024$ by exact test, four with $P < 0.1$) (Table 4).

The largest mean DMM daily changes were from tree C, a tall, not especially exposed *Mallotus*. The smallest daily changes were from trees G and H, a large well-exposed hard-barked *Dryobalanops* and a tall *Bhesa*. In proportional terms, the largest changes are from tree E, a ragged crowned *Aglaia*, while the smallest are from tree G, a large *Dryobalanops*. This sample is too small to generalize how flexing relates to size, species, crown form, and exposure, but daily girth changes of 0.5–2 mm are unexceptional during this generally cloudy period.

The DMM approach consistently registers larger daily changes than the dendrometers. The difference between mean daily girth changes for the two methods is just under 1 mm: tree B, 0.77; tree C, 0.98; tree D, 0.92 mm. The magnitude of each daily change recorded by the two different techniques is plotted for the three trees in Fig. 2. The scatters, especially for tree B, suggest a possible stick-slip dendrometer threshold, where only large changes are consistently detected. The comparison of largest versus smallest records over the full period involved DMM changes of about 2 mm, with one tree, B, giving a value of 6 mm. The differences for the dendrometer bands are less (Table 3).

How do DMM and dendrometer approaches compare if only growth across days is considered? The cross-method correspondences were examined separating morning and afternoon series (Fig. 3). The strength of these relationships rank in order of actual growth (tree B > tree D > tree C). Tree C shows little correlation. The Pearson correlations for tree B are almost equal for afternoon and morning data (afternoon, $r = 0.884$; morning, $r = 0.891$; $P < 0.001$ for both, $n = 12$) and also for tree D (afternoon, $r = 0.693$, $P = 0.12$; morning, $r = 0.509$, $P = 0.09$), although the overall relationship is weaker. For tree B, regression of the dendrometer versus DMM measures shows a 95% confidence interval on a gradient of 0.297 to 0.649 and 0.271 to 0.573 for afternoon and morning, respectively; for tree D, the respective ranges are 0.119 to 0.772 and –0.061 to 0.694, i.e., 1:1 is excluded in all four. However, Fig. 3 also indicates that during periods of rapid daily expansion, both methods can show equivalent changes, with tree B dendrometer tracking the DMM results for the second half of the observation period.

Discussion

Overview

The DMM approach offers a technically simple means to record stem girth changes with submillimetre precision and accuracy. This reveals morning–afternoon differences in girth of around 1 mm. Timing and relationships with weather suggest, as expected, that stem water status is involved. Band-dendrometers detect some of these changes but underestimate their magnitude.

Tropical stem shrinkage is not a new discovery (e.g., Karling 1934). I suggest two explanations for recent neglect. First, oversight: studies of tree growth in the tropics have neglected within-day (diurnal) patterns. Second, inappropriate methods: band-dendrometers have become the "technique of choice" for precision growth studies.

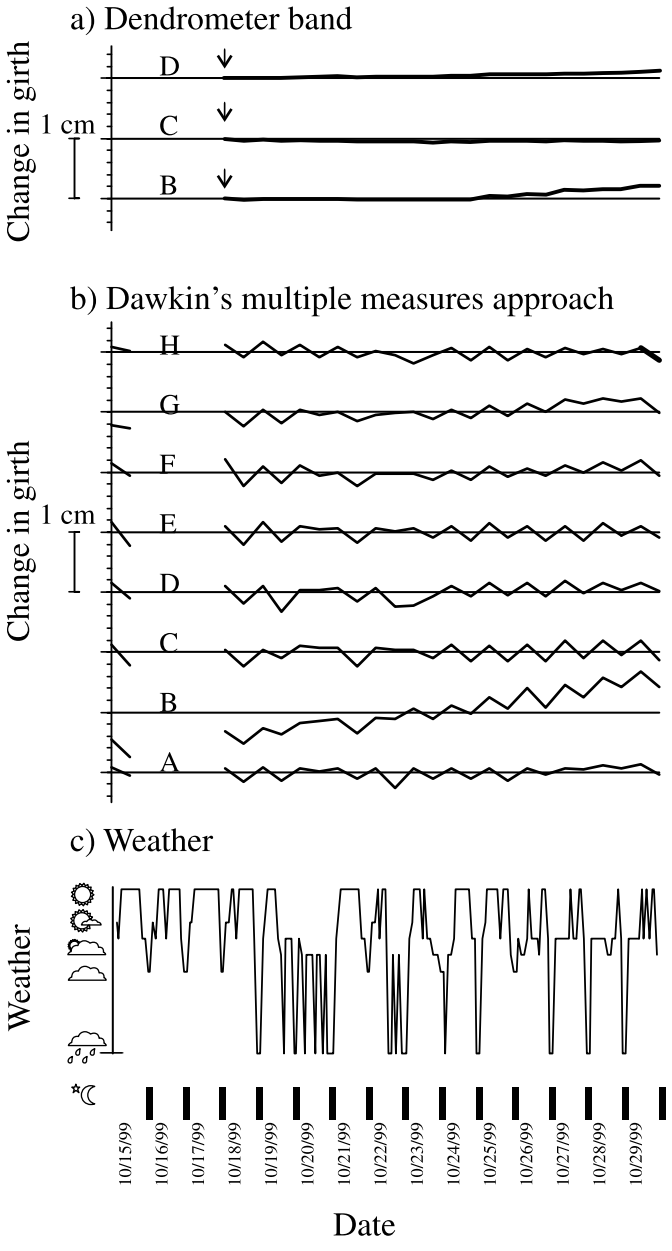
While past observations and the recent study are limited, they imply that daily stem size changes can be large (>0.3 mm in diameter) and that band methods can underestimate them. Such implications deserve careful appraisal, in terms of both general growth studies and specific dendrometer limitations.

Scales and uncertainties

Do daily size changes matter in normal growth assessments? Currently, we can only speculate about how such effects might influence data from general inventory methods (with tapes, calipers, etc.). Size fluctuations might be viewed as simple "noise" spread randomly across a population. Yet, tree measurement sequences are not random, and measure-

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Fig. 1. Summary of the data from (*a*) the twice-daily dendrometer band records, (*b*) the twice-daily Dawkins (1956) multiple-measures approach (the first two records were trials several days before the main study period; these data are not used in the main analyses but are included here), and (*c*) the hourly, by day, and two per night weather records. Note that the horizontal scale for each is aligned by days but not hours. Capital letters denote the trees as in Table 2.



ment periods are never matched for time and weather conditions. Systematic biases are probable.

Diameter growth in tropical trees is usually around 1–10 mm/year (Worbes 1999). In the Kalimantan observations, the daily flexing effect is about 0.3 mm in diameter, and mean growth is 2.8 mm/year (SD = 0.14, all species combined, stems ≥20 cm in diameter, twenty-four 1-ha plots for 2 years, $n > 2000$; CIFOR, unpublished data). A system-wide bias of 0.3 mm diameter would represents about 10% of yearly growth. At the individual stem level, the situation may be worse: the distribution of growth records in any census period is strongly skewed, with a median well below the mean (Sheil 1995). Biases caused by flexing may cause larger proportionate error on slow-growing stems than is apparent using stand mean data. In addition, most yield summaries reported from forest plots can be attributed to changes measured in just a few larger trees: such stems are generally well exposed to transpiration demands.

Such biases can influence yield studies. We can illustrate this using $\Delta\text{volume} \approx \text{volume} \times 2\Delta\text{girth}/\text{girth}$ (Δ means "change in") (Sheil 1997). Assuming a forest with an above-ground volume of 400 m^3/ha and a systematic stem size bias of 0.1% gives approximately 0.8 m^3/ha, while a 0.3% bias implies approximately 2.4 m^3/ha. These are not negligible errors.

Bias seems plausible when the absolute growth measurements are themselves small (e.g., short-term growth studies, slow-growing stems) and when climatic conditions differ between measures. The contribution of all such biases will be diminished over longer measurement intervals when true growth contributes more. For short-term (e.g., monthly) studies, large proportional biases appear to be possible. Artifacts may also influence investigation of weather–growth relationships. These concerns, while speculative, justify further evaluation.

Growth and season

The observation that wetter periods are sometimes associated with lower growth has generated several explanations, including the effect of cloud cover (Clark and Clark 1992, 1994; Raich et al. 1991), altered competition, and actual water availability (Bullock 1997). Trees also allocate energy to new leaves, fruits, etc., on seasonal and weather-related cues, and such phenology likely influences stem growth. Such proposals remain debatable, but I add the suggestion that ephemeral patterns of stem shrinkage may play a role. In full foliage and bright sunshine, stem water can be greatly depleted. Similar effects could also explain the opposite pattern of higher wet season growth (e.g., Silva et al. 2002), with swollen stems being measured more often in wet conditions under heavy cloud cover. Patterns will likely depend on many factors, including local weather, tree behavior, and measurement practices.

When is the best time to measure growth?

When should trees be measured for accurate growth assessment involving longer periods (≥1 year)? I have previously suggested for semideciduous forests that wet season measures are more perturbed by moisture (deficits and availability) and by phenological events (flowers, fruit etc.) impacting true growth. Dry season quiescence reduces growth variance (Sheil 1995, 1997). Karling's (1934) observations concur (Table 1): daily changes were reduced when soil moisture was limited and increased in bright conditions when water was available. Baker et al. (2003) disagreed. They found that interyear variance in recorded growth was higher between dry rather than wet seasons. However, this result remains debatable, given the use of dendrometer bands, with a failure to detect diurnal changes, an unknown influence of "settling" in dry season measures, and an unusually strong drought during their measurement period.

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Table 3. Tree size and magnitude of daily girth changes (differences between morning and afternoon) and those over the whole period.

	Dendrometer bands			Dawkins' (1956) multiple measures							
Tree	B	C	D	A	B	C	D	E	F	G	H
Mean girth (cm)	174.2	151.4	124.9	76.2	174.2	151.4	124.9	87.5	160.8	179.4	161.0
Mean daily change (mm)	0.054	0.100	–0.013	0.792	0.821	1.083	0.905	1.000	0.917	0.667	0.698
Mean %	0.003	0.007	–0.010	0.104	0.047	0.072	0.072	0.114	0.057	0.037	0.043
Max. (mm)	0.250	0.300	0.200	1.625	1.571	1.571	2.143	1.625	2.250	1.250	1.125
Max. %	0.014	0.020	0.016	0.213	0.090	0.104	0.172	0.186	0.140	0.070	0.070
Min. (mm)	0.000	–0.100	–0.200	0.125	–0.143	0.143	–0.714	0.250	0.000	–0.125	–0.625
Min. %	0.000	–0.007	–0.016	0.016	–0.008	0.009	–0.057	0.029	0.000	–0.007	–0.039
No. of zeros	7	2	8	0	0	0	1	0	1	0	0
No. of negatives	0	1	3	0	1	0	1	0	0	1	1
P (sign test)	0.031	0.011	0.94	0.00024	0.0032	0.00024	0.0058	0.00024	0.00049	0.0032	0.0032
Whole period max.–min. (mm)	2.300	0.600	1.200	2.000	6.000	2.143	2.571	1.875	2.250	2.375	1.750
Whole period max.–min. %	0.132	0.040	0.032	0.263	0.344	0.142	0.206	0.214	0.140	0.132	0.109

Table 4. Relationship of daily differences (morning minus afternoon) by Kendall's τ rank correlation (n = 12 and quoting two-sided probability (P) with values <0.1 with an asterisk) between stems and with a weather index.

Tree		B	C	D	E	F	G	H	Weather index
A	τ	–0.167	–0.139	0.492	0.222	0.248	0.437	0.293	0.244
	P	0.477	0.563	0.034*	0.350	0.288	0.064*	0.220	0.290
B	τ		0.740	0.079	0.265	0.128	0.374	0.000	0.551
	P		0.002*	0.728	0.256	0.577	0.106	1.000	0.015*
C	τ			0.083	0.414	0.284	0.424	0.139	0.575
	P			0.723	0.084*	0.227	0.074*	0.563	0.013*
D	τ				0.586	0.173	0.176	0.230	0.109
	P				0.011*	0.445	0.442	0.322	0.629
E	τ					0.476	0.517	0.427	0.436
	P					0.040*	0.028*	0.072*	0.058*
F	τ						0.645	0.612	0.313
	P						0.005*	0.009*	0.166
G	τ							0.538	0.572
	P							0.023*	0.012*
H	τ								0.179
	P								0.438

Mechanics of band-dendrometer error

Band-dendrometers can detect changes, especially when the true extent is large, but they appear to be ineffective in recording the magnitude of short-term size fluctuations. In the field trial, longer settling delays might have allowed improved responses (Bower and Blocker 1966; Keeland and Sharitz 1993). Two of three bands detected growth quite effectively, even though the relationship was significantly less than 1:1. Figure 3 hints that in some periods of continuous growth, the correspondence is good. When compared against the DMM measures, there was no consistent improvement in accuracy during the morning, when stems are more likely to approach maximum size, than in the afternoon. This summary does not fundamentally challenge the role of well-settled band-dendrometers in longer term growth studies, but it does question their accuracy when both expansion and shrinkage are involved. It remains plausible, over longer time periods, that band methods provide a good approach to recording recent "maximum sizes", thus reducing moment to moment error introduced by stem shrinkage.

Despite known problems (e.g., Bormann and Kozlowski 1962; Kozlowski and Winget 1964; Keeland and Sharitz 1993), band-dendrometers remain popular in precision monitoring. The DMM method, although simple and accurate, is labor intensive and is practical for only relatively few stems at a time. Bands are relatively cheap and once installed are quick and easy to use. The suitability of dendrometer bands for different purposes and contexts remains questionable, even in temperate literature. For example, they are advocated for stem water monitoring by Holbrook (1995).

Reviewing potential reasons for band-dendrometer errors should help clarify when the approach is unsuitable and if improvements are possible: providing theoretical underpinnings for methodological investigation. Three possible errors are considered here: thermal expansion, band elasticity, and band–stem friction.

Thermal expansion

The thermal expansion of the band is 11.2×10^{-6} $m \cdot m^{-1} \cdot {}^{\circ}C^{-1}$ (Agricultural Electronics Co. 1996). This provides around 0.1 mm on a 1-m girth after a 10 °C tem-

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Fig. 2. Relationship of daily changes recorded by the two assessment methods on stems B, C, and D. The dotted line indicates equivalence.

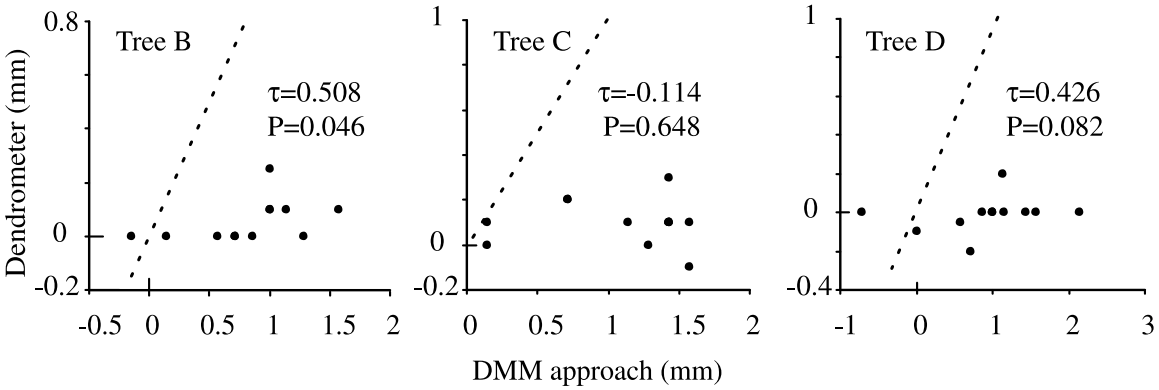
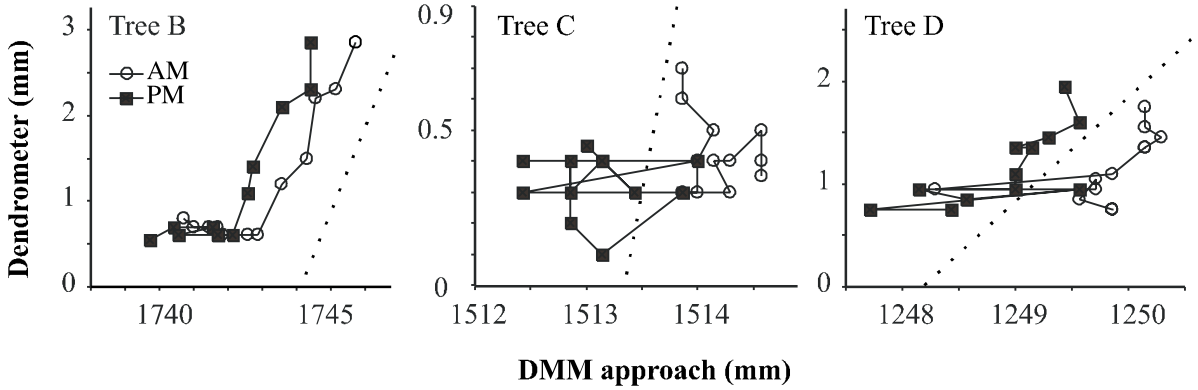


Fig. 3. Relationship of overall changes recorded by the two assessment methods comparing morning (AM) and afternoon (PM) series on stems B, C, and D. The dotted line indicates the gradient of a 1:1 correspondence.



perature rise. If sunshine were to fall directly on (half) the metal band, an additional 0.3 mm/m seems plausible: similar in magnitude to the daily flexing. However, this slack would cause overestimation of daily shrinkage, not the underestimation observed.

Band elasticity

Girth changes are translated by an "inelastic" band to the sliding gauge. However, as shifts in the band require a change in tension, and no material is perfectly inelastic, some stretching must occur. Assuming a Young's modulus of 2.0×10^{11} N/m^2 (steel), a force of 1.22 N (the dendrometer spring strength), a tree of 3-m girth, and a band of cross section of 1 mm^2 suggests a stretch of less than 0.02 mm. The changes in tensile forces needed to register 0.1-mm length differences would be several times higher than the near-fixed forces that occur in normal operation.

Friction

Friction may hold a band without slipping as a stem shrinks. As the band is relatively inelastic, the required surface to surface pressure is presumably maintained by the elastic rebound of the stem as tension declines. "Missing band length" may derive from differences in stem deformation, and associated band lengths, under alternative limiting (no-slippage) tension patterns (Fig. 4). This idea can help predict error and its dependencies.

A standard result in analytical mechanics shows that a band, wrapping a fixed object, with a tension T_L applied at one end can be held static by a lower tension at the other end. The relationship between T_L and T_S, the lowest sufficient holding tension, is given by

$$[1] \qquad T_L = T_S e^{\mu\theta}$$

where θ is the completed angle of wrap (radians), and μ is the coefficient of friction. Given this relationship, and an expression for how each stem deforms under pressure, we can estimate the length differences that can occur between a limiting situation under stem expansion and contraction (Fig. 4).

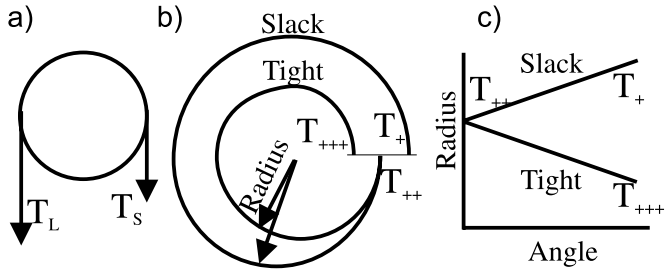
I assume a circular stem section and linear stem elasticity. The band radius, R, is variable and is defined as relaxed radius, R_r, minus radial deformation, ΔR, i.e., $R = R_r - \Delta R$ ($\Delta R << R_r$). Including elasticity gives $\Delta R = -Fk\lambda/(2\pi R_r)$, where F is radial force, λ is a spring constant, and k is the depth of springy tissue. I shall describe two models that differ only in how stem elasticity relates to stem size. In the first, model 1, deformation per unit pressure is proportional to R_r ($k = R_r$): as stems get larger, absolute deformation increases. In the second, model 2, elasticity is confined to a layer of constant depth, and deformation per unit pressure is independent of R_r (k is a constant $<R_r$). Integration of the two path lengths over the wrap angle, θ, provides an expression for band length changes between maximum tension and maximum slack without slippage, $L_T - L_S$:

Model 1:

$$L_T - L_S = \lambda T_S(e^{\mu\theta} - e^{-\mu\theta})/(2\pi\mu^2)$$

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Fig. 4. Tension gradients can lead to band length differences. (*a*) A band held static by friction can have different tensions at each end. A standard formula in mechanics provides the relationship between these in the limiting case. (*b*) Alternate tension gradients along the band cause different "spiral" lengths between the two limiting scenarios (illustrated here for the same "true" stem diameter). As the stem shrinks, the constant spring force (T_{++}) is the higher of the tensions (the other end is T_{+}), but if the stem expands, the spring eventually becomes the lower tension, and the other end is higher (T_{+++}). (*c*) A formula can be derived to predict error based on angle of wrap and linear stem deformation.



Here, R cancels out during simplification, so $L_T - L_S$ is independent of R, proportional to λ and T_S, and shows a complex relationship with μ and θ.

The equivalent model 2 derivation yields

Model 2:

$$L_T - L_S = \lambda k T_S(e^{\mu\theta} - e^{-\mu\theta})/(2\pi R_r \mu^2)$$

Thus, model 2 is just as model 1 multiplied by k/R, and so, $L_T - L_S$ is now inversely related to stem size. The true situation may lie between the two models.

Can such models apply to those band-dendrometers held in place only by spring tension (e.g., Liming 1957)? The Ghana and Sumatra examples in Table 1 are of this type. The physics are similar, so I believe that the same problems occur. A technical argument can be proposed: the full band can be replaced with a model where the middle of the band is fixed, yielding two half-bands with a "free" end. The various expressions that we have developed for the full circuit expression can be used for each half and added (i.e., $\theta \approx \pi$, rather than $\approx 2\pi$, and the path difference is doubled for the full band length), i.e., scenario 1 is now

$$L_T - L_S = \lambda T_S(e^{\mu\theta} - e^{-\mu\theta})/(\pi\mu^2)$$

and scenario 2 is

$$L_T - L_S = \lambda k T_S(e^{\mu\theta} - e^{-\mu\theta})/(\pi R_r \mu^2)$$

Thus, the expressions are similar. What do these predict? (*i*) Each tree–band combination has a threshold for detectable size fluctuation involving alternating expansion and contraction, (*ii*) this threshold is dependent on bark friction and degree of stem plasticity (softer stems and bark will give bigger errors, and reducing friction in the band to bark contact will improve sensitivity), (*iii*) stronger springs will cause proportionally larger errors (more friction, more deformation), and (*iv*) as absolute error may be largely independent of stem size (model 1), or even inversely related to it (model 2), larger trees will have smaller proportional errors. Note that according to predictions *ii* and *iv*, large stems, with hard firm bark, as chosen in our field study, may yield the smallest errors. All of these predictions are amenable to future investigation.

The proposal that bands may normally maintain a subslippage tension gradient may be relevant in other ways. A tense band may slowly relax over time, e.g., with vibration and moisture. Reich and Borchert (1982) found up to 1 mm of shrinkage for *Tabebuia* in Costa Rica. Baker et al. (2003) found seasonal shrinkage of over 0.7 mm in Ghanaian *Celtis* over the 1997–1998 El Niño. Baker et al. (2003) also evaluated band settling by placing a dendrometer on a living butdamaged tree that showed no growth over the measurement period. They found no change in stem diameter over 2 years and suggested that long-term settling is therefore "not a concern". However, such settling is likely a very different physical process on a vigorous size-fluctuating stem.

A possible fix

Few precision approaches are as cheap and simple as the band-dendrometer, so improvements are worth investigating. If error in band methods is principally due to unequal tension patterns, removing associated variation should improve accuracy. I predict that a momentary tension increase "sufficient to guarantee slipping", just prior to reading, will standardize tension patterns and improve accuracy. Such a fix appears to be technically simple, especially for a firmly attached dendrometer, and can be investigated further as a means of tracking true diameter changes.

Conclusions

According to previous band-dendrometer studies, daily fluctuations in tree diameter are generally small, less than 0.2 mm. However, other studies noted much larger changes. These changes seem to have been ignored in tropical growth studies.

The DMM approach shows daily variation in girth of about 1 mm in all eight stems examined in Borneo. Changes are larger in bright conditions. These changes do appear to be of sufficient magnitude to interfere with the accurate evaluation of woody growth under some circumstances, although this requires further study. Just as long-term sea level changes would be difficult to assess from intermittent records if tides were unrecognized, the evaluation of tree growth must consider both long- and short-term fluctuation processes. Misinterpretations seem especially likely when true growth over any measurement interval is small, or when measurements take place under different conditions. Patterns of diameter change, and associated growth assessment errors, are complex and require further study.

Dendrometer bands can considerably underestimate stem changes involving alternate shrinkage and expansion. A likely explanation is that friction holds the band fixed while stems shrink. Theoretical analyses suggest that such errors depend on a stem's elastic deformation and the friction of bark–band contact. Any process ensuring consistent band tensions prior to reading should improve dendrometer accuracy.

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