Tropical Deforestation Alters Leaf Wetness Duration

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May 5, 2020

Abstract

In tropical rainforests, large-scale deforestation is considered one of the biggest threats to the environment. This threat has been shown to contribute to a loss of biodiversity, carbon storage, and hydrological services such as erosion control, streamflow regulation, and water quality. Interception losses are a much higher proportion of the water budget in areas such as moist tropical forests, where precipitation can exceed 3000 mm per year. Given interception is higher in forests with large canopy storage capacity than low stature vegetation, we aimed to identify the relative differences in leaf wetness duration in Costa Rican premontane forest and adjoining cropland. Biomass alone determines maximum interception storage, but does not determine interception loss, since storage can saturate with relatively small rain events. We aimed to determine if leaf wetness duration (LWD) is positively correlated with interception. Forest leaves stayed wet five times longer than the crop fields, 487 $\pm$ 41 minutes compared to 94 $\pm$ 37 minutes. Within crop species, papaya took twice the time to dry than taro and sweet potato (137 $\pm$ 51 in contrast to 73 $\pm$ 23 minutes). Crop heights were well correlated with dry-down rates ($r^2 = 0.98$). These results suggest the possibility of higher runoff and alteration of rainfall recycling in the humid tropics, following tropical forest conversion to cropland.

Introduction

The relationship between forest cover and the hydrologic cycle is complex. A growing scientific consensus considers that stream flows in temperate forests tend to have smaller peaks during flooding and sustain higher base flows during drought compared to non-forested streams, but the same dynamics do not apply in the same way in the humid tropics (Brown et al., 2005). Furthermore, potential differences in stream flows are associated with a variety of drivers, including the partitioning of evapotranspiration (Good et al., 2017). Rainfall interception is of even greater importance in the humid tropics, as these regions experience frequent wet-dry cycles, considerable canopy interception, and high evaporation of intercepted precipitation, ranging from 10-30% of gross rainfall (Bruijnzeel and Scatena, 2011; Calder et al., 1986).

Rainfall interception has been widely studied in humid tropical systems (Bruijnzeel and Scatena, 2011; Chu et al., 2014; Giambelluca and Gerold, 2011; Holwerda et al., 2011; Safeeq and Fares, 2014; Takahashi et al., 2011). In most cases, deforestation scenarios have been associated with reduced interception, increased surface runoff (Maris, 2015; Panday et al., 2015), and exacerbated streamflow peaks and low flows (Brookhuis and Hein, 2016; Bruijnzeel and Scatena, 2011; Laurance, 2007; Ty et al., 2011). Research that examines hydrological shifts accompanying vegetation changes in humid areas is directly applicable to similar regions. In fact, many reviews of such cases (Bowling et al., 2000; Brooks et al., 2012; Bruijnzeel and Proctor, 1995; Bruijnzeel, 2004; Calder, 2001; Eisenbies et al., 2007; FAO, 2005) broadly generalize the mechanisms by which forests may reduce chances of floods: through increased interception, evaporation, and reduced overland flow of water.

A study in Venezuela reported a sevenfold reduction in foliage interception between tropical montane forest and pastureland paired with higher surface runoff (Ataroff and Rada, 2000). Asdak et al. (1998) found a similar decrease with reduced canopy cover in progressively more open forest areas: closed canopy, partial canopy, and canopy gap, respectively. They proposed discontinuous canopy structure, rather than deforestation, as the cause of the reduced evaporation. Similarly, a modeling experiment in Costa Rica examined scenarios of sequentially more deforested areas, from pristine forests to extreme deforestation, and found that although water yield was not significantly altered, forest cover was inversely related to runoff peaks and low flows (Birkel et al., 2012).

Canopy interception (I) differs by orders of magnitude over very short distances in heterogeneous natural forests (Teale et al., 2014), making it difficult to capture spatial variation adequately to produce reliable estimates. I is driven by biomass, whereas canopy evaporation (E) is driven by canopy structure (in turn driven by how well air mixes in the canopy). Leaf wetness duration (LWD) is affected by both structure (Kume et al., 2006) and biomass, since higher leaf area and thus I generates humidity in the canopy that slows down E. We expect LWD is highest in canopies with high I, but the magnitude difference in LWD is much lower than differences in I.

We use a case study in a Costa Rican premontane tropical forest, a high precipitation environment, to evaluate canopy wetness properties due to conversion from mature forest to monoculture row crops. One of our objectives was to learn more about differences in disturbed forests with gaps, indicative of selective logging, which is common in this region. Further, we wanted to compare between forest and commonly grown crops in the region. This helps establish to what degree taller, more complex vegetation intercepts more moisture and stays wet longer than short-statured crops, releasing water to the atmosphere rather than it running off and increasing stream flow. Our final objective was to determine whether canopy height can be used to predict LWD.

Materials and Methods

2.1 Site description

This study was conducted near the town of San Isidro de Peñas Blancas, San Ramón canton, Alajuela province, Costa Rica, on land adjacent to the Children's Eternal Rainforest and the Texas A&M University Soltis Center for Research & Education (10°22'59.1"N, 84°37'06.4"W). All sites were located in the middle Chachagua watershed within 1.7 km from the Soltis Center. The elevation ranges 400-500 m above sea-level and the area is composed primarily of either mature premontane forest (Holdridge, 1966), or converted agricultural land. Average annual temperature is 24 ºC, while precipitation averages 5000 mm per year, with monthly rainfall maximums of 430 mm during the rainy season and 130 mm in the dry season. This qualifies the area as moist tropical forest (D'Odorico et al., 2010).

The study compared microclimate within and under mature forest canopy to microclimate within the canopy boundary layer of three crop sites. We further stratified the forest into two categories: closed canopy (mature forest), and open canopy (in the case of a clearing formed from a wind downburst or a natural forest gap) to account for different canopy structures from dense tall forest to dense low-stature crop and including two additional low-stature crops with more open canopies. The forest is a mix of primary and secondary tropical vegetation, predominantly composed of trees in the Sapotaceae (hibiscus), Moraceae (fig), and Malvaceae (milkwood) families (Miller et al., 2013). The closed canopy forest site was approximately 30 m in height and accessed by a 40 m micrometeorological tower.

The three crop sites were representative of even-aged monoculture plots of papaya (*Carica papaya*), taro (*Colocasia esculenta*), and sweet potato (*Ipomoea batatas*) fields. These vegetation types were chosen due to their economic value to Costa Rica and proximity to the forest sites. Within crops, the average canopy heights were 1.8, 1.3, and 0.7 m, respectively for papaya, taro, and sweet potato. Papaya had a sparse open canopy with large intercanopy gaps. Taro was grown more densely with smaller gaps between canopies, and sweet potato was grown in a dense layer of continuous vegetation near the ground surface.

Measurements within forests were collected in both 2011 and 2014, while the crop site measurements were added during June to July 2014. Within-forest comparisons include measurements from both 2011 and 2014, while comparisons between forests and crops were restricted to 2014. Forest conditions did not change significantly between measurement years.

2.2 Microclimate measurements over the crops

Continuous measurements of air temperature (°C), relative humidity (%), and leaf wetness (%) were averaged every ten minutes. Sensors were mounted on an Onset Computer Corporation HOBO U30 datalogger and Remote Monitoring System (Bourne, MA, USA) placed in the center of the plots. An air temperature and humidity sensor (HOBO S-THB-M00x) was mounted at approximately average canopy height for the three crops. An S-LWA-M003 capacitive grid leaf wetness sensor (Onset Computer Corporation, Bourne, MA, USA) was mounted parallel to the ground at 1.62 m (papaya), 1.41 m (taro), and 0.95 m (sweet potato) outside the canopy. To record total precipitation (mm) every 10-minutes, a tipping-bucket rain gauge (HOBO S-RGA(B)-M002, Bourne, MA, USA) was installed near the top of each station ˜1.9 m above the ground.

2.3 Leaf wetness duration over both crops and forest

Leaf wetness in the covered forest condition was measured using an LWS-L dielectric LWD sensor (Campbell Scientific, Inc., Logan, UT, USA), which is based on the same dielectric principles as the Onset LWA sensors. Rain (or more rarely, condensed fog) was collected on the leaf wetness sensor and a current proportional to the water amount was detected by the data logger. The two sensor types, Onset in the crop fields and Campbell in the forest, were manually calibrated at saturation and fully dry end points. For the crop threshold determination, saturation was 100% and dryness was 15%, based on previous work at this site (Aparecido et al., 2016). In wet tropical rainforests, some portions of the canopy can remain wet for a significant fraction of daylight hours (Aparecido et al., 2016). The forest LWD measurements were taken at five heights on the micrometeorological tower, at 5, 12, 24, 34, and 40 m. For the LWS-L, the wet threshold was set at 400 and the dry threshold at 125 (dimensionless units), according to the most consistent fit for the data based on methodology in Aparecido et al. (2016).

2.4 Data Analyses

To meet the criteria for a dry-down event, the LWD sensor had to register 100% saturated and decline to the threshold dry level of 15% without an increase of at least 2% wetness over ten minutes. This stipulation ensured that an errant water droplet did not discount a dry-down event but eliminated breaks in precipitation during long storm events. These inclusion criteria were applied across sites and years, and a total of at least nine dry-down events that were representative of each vegetation type were used in the analysis. The data below the dryness threshold were rescaled as 0% wet.

We also compared the rate of leaf drying between crop sites and forested conditions. For each 10-minute time point throughout the dry-down event, the differences in leaf wetness between sites were compared across all replicate events using a paired t-test (α-value of 95%). Dry-down curves were best-fit with logarithmic trend lines using the format $y = -m(\ln)x + b$ where m is the slope and b is the y-intercept. We compared mean least squared differences in dry-down slopes to canopy height using a back-transformed linearized equation derived from the logarithmic trends. To allow transformation, we first increased all the data by two orders of magnitude and converted the dry-down rates to positive values. Analysis of transformed data reduced variance and kept the resulting data within the same order of magnitude.

To compare drying times between vegetation types, an analysis of variance (ANOVA) model was applied for all paired treatment combinations. Afterwards we applied a Tukey's post-hoc test to separate the conditions into like groups by comparing their means. Drying times were considered different between groups at $p < 0.05$, and coefficient of determination (R^2) was used to indicate model fit.

Results

3.1 Comparison of relative humidity between crop types

For every 20% increase in RH above papaya, taro and sweet potato increased by 19.85% and 19.84%, respectively, throughout the three-week period in 2014 ($p < 0.001$, see Figure 1); however, while the differences in RH are statistically significant, their magnitudes potentially fall within the measurement uncertainty of the sensor. We chose papaya as the control plant because it has the highest average canopy height. We observed many time points at which taro and sweet potato were 100% humid while the air was not fully saturated in the papaya field: 11% and 15% of the time, respectively.

3.2 Comparison of Dry-Down Curves and Leaf Wetness Duration between Vegetation Types

After rain ceased, the period of dry-down for all crop types tended to follow a logarithmic decay (see Figure 2). Over the period from saturation to fully dry, there was a very good fit to the linearized log trends of the back-transformed data for all dry-down events (R^2 [?] 0.93), and the slopes differed greatly between vegetation types ($p < 0.05$).

The closed-canopy forest stayed, on average, wetter longer than any other vegetation type (see Table 1 and Figure 3, $p < 0.05$). Closed-forest leaf wetness dried at a relatively consistent rate after the initial 100 minutes, when the rate became less steep. Based on this observed shift in drying rate for the forest, a separate analysis of the first hour after the event was conducted. When examining the initial drying period of one hour, a linear fit was most appropriate. Closed forest had a less negative slope than all other locations, –0.52% wetness lost per minute compared to –1.22 ± 0.07% per minute. Finally, forests took ˜250 minutes longer to reach the level of dryness observed in crops after only one hour (see Figure 2 and 3).

Papaya retained wetness longer at a lower level after the initial period of similar drying, instead of continuing to dry at a uniform rate. When comparing the three crops to each other individually, there is an apparent inflection point before which the non-transformed slopes of the three crops were –0.12, –0.11, and –0.10% per minute, respectively, all very steep with similarly high goodness of fit (R^2= 0.93, 0.94, 0.87 for papaya, taro, and sweet potato). However, at 50 minutes, papaya begins to have a slope of –0.02% per minute, less than 1/7 of the rate of change as during the first hour (Figure 2), and LWD extends much longer than for the shorter canopy crops. Drying rates were remarkably similar between taro and sweet potato ($p < 0.05$, see Figure 3), which is surprising considering sweet potato is a ground-cover crop and taro had a more distinctive canopy up to 1.3 m in height.

The mean LWD in closed mature forest of 339 ± 174 minutes was 3.6 times greater than crops, which averaged 94 ± 37 minutes, and more than 2.6 times the duration of open forest (129 ± 68 min, see Figure 3). Papaya LWD behaved more similarly to open forest than to the lower crops despite being similar in height to the crops, drying almost twice as slowly (LWD = 137 ± 51 min) as taro and sweet potato (LWD = 73 ± 23 min, all with $p < 0.01$). The dates and time of day for each dry-down event as well as the event duration are listed in Table 1 by vegetation type.

As height increased, the slope of the dry-down curve flattened, as is expected if the higher canopy and inter-canopy space retain moisture longer after a dry-down event. We found strong evidence that height could be used to predict LWD (R^2 = 0.94, see Figure 3). For short-stature vegetation around 1 m, a 1 m increase in height extends dry down rates by 18%, whereas for taller vegetation around 10 m, a 1 m increase in height only extends dry down rates by 0.17% per minute (Figure 4).

Discussion

In very wet tropical systems, the use of LWD as an additional variable to study the impact of deforestation on available water in the forms of canopy water storage capacity, intercepted rainfall, and leaf evaporation appears to have merit, as it relates to canopy properties that these other variables do not fully capture. A five-fold longer LWD in forest than crop fields is consistent with previous findings, demonstrating that

LWD varies depending on position in canopy and species tested (Sentelhas et al., 2005). Although we noted significant differences in LWD between short and tall statured crops, we were unable to discern a difference between small crops using comparisons between only a few rain event dry-down cycles. However, we report a predictive relationship that can better differentiate how small changes in canopy heights, even in short-statured crops, can lead to incremental changes in LWD.

Our results also demonstrate that LWD can contribute to the larger question about the impact of land use on hydrology, particularly in very wet systems with high interception fractions. Premontane tropical forests undergo frequent wet-dry cycles, thus the fraction of the water budget affected by interception is relatively high compared to temperate regions. At this site, vegetation below the forest canopy was wet up to 85% of the time (Aparecido et al., 2016). Increased LWD is indicative not only of higher surface area of leaves intercepting precipitation, which translates to less water reaching the ground surface and more potential for water storage on the canopy, but also the aerodynamic properties that allow air in the canopy to mix, which lets leaves re-wet repeatedly throughout an event and between events that occur sequentially. LWD may therefore be a key covariant with I and E that could improve predictions of water budgets in these forests and determine the effects of deforestation on stream flow more precisely.

Tropical deforestation has been found to impact stream flow dynamics. In Mexico, for example, deforestation of cloud forest was associated with more erratic flows during the dry season (García Coll, 2002). Bruijnzeel and Scatena (2011) also concluded that conversion of lower montane cloud forests will likely considerably increase runoff locally due to low cloud water interception. The shorter LWD we observed in the crop fields show similar findings.

We further examined wetness differences between crop types by comparing RH data from sensors in the crop boundary layer. We observed the apparent conundrum that papaya humidity was lower, but it still took a long time to dry. It is reasonable that the leaf surface properties held water longer, supported by the fact that the first hour dried similarly as taro. Although leaf wetness sensors do not mimic leaf surface properties, the extended drying times in papaya suggest the leaf surfaces might trap water and release it more slowly than in taro, which has smoother and waxier leaves. Both leaves are much larger than sweet potato leaves. Furthermore, because papaya plants are more heterogeneously spaced in wide rows, the turbulent mixing ratio is higher in the space surrounding that crop. That could explain why usually papaya interspaces were less humid than taro's or potato's. Increased turbulent mixing within more widely spaced crops may counteract longer LWD to some extent, as seen in Bailey and Stoll (2013) and Bailey et al. (2014). Sweet potato and taro have lower roughness coefficients than the taller and structurally more complex papaya, creating a more defined boundary layer than in papaya, which acts as a pocket of humid air at the canopy (Raupach, 1994). Nonetheless, we postulate that this dampening boundary layer effect combined with greater surface area of papaya leaves could explain the net effect of longer LWD in papaya than shorter crops. Further work is needed to understand the relative importance leaf properties (size, texture), canopy properties (shape, spatial orientation), and total surface area on the water budget.

Our results demonstrate how the spatial orientation of plants in tall canopies can affect drying rates. Even though within-crop biomass differences were much smaller than biomass differences between forests and crops, LWD differed by less than an order of magnitude. Asdak et al. (1998) found that rainfall interception loss decreased with reduced canopy cover in progressively more open forest areas, which approximates our result from open canopy forest conditions. Thus, forest fragmentation is likely to have an effect on evaporation through not only decreased interception, but also faster drying rates. We found statistically indistinguishable trends in LWD between papaya and open canopy forest, suggesting that even modest canopy gaps can effectively alter the hydrologic characteristics of otherwise intact forests. This has interesting policy implications, because it suggests that agroforestry, even of thin short-lived trees like papaya, may provide similar hydrological services to that of open forests. This is an important issue to highlight, as there are many programs focusing on agroforestry in the tropics (Mercer, 2004).

Recommendations

Given the growing number of policies citing hydrological benefits of forest conservation in the tropics, there is a need for more tropical case studies of hydrological effects accompanying forest cover changes. Our contribution examines leaf wetness in relation to crop type and vegetation height to better understand hydrologic reactions to deforestation in premontane tropical systems with much higher (~5000 mm) annual precipitation than in previous studies. Although this insight about LWD was not directly compared to direct measures of canopy interception or evaporation, the great relevance of our findings for extremely moist environments justifies further study. Particularly in watersheds in tropical regions undergoing deforestation, there is a need for more detailed water budgeting between forests and agricultural land.

The additive hydrological effects at the watershed scale deduced from our results suggest broader landscape changes accompanying deforestation, although inherent complications exist from scaling between leaf-level and watershed-level effects (Jarvis, 1995). Furthermore, these results are more informative with intense removal of forest cover, since severe reductions in leaf area have more potential to alter interception. And yet relatively small canopy gaps similar to those found with selective logging led to drastically shorter drying times. LWD may not be as important in temperate climates, but in the humid tropics there is potential for this parameter to indicate an effect of deforestation on streamflow, as a relatively high interception of precipitation has been demonstrated (Wang et al., 2007, Good et al., 2017) compared to arid systems where soil evaporation accounts for more evaporation than intercepted precipitation (Cavanaugh et al., 2011). It is reasonable to assume that interception and LWD are positively related, and that post-rainfall evaporation is faster in lower stature vegetation than tall canopies. However, all else equal, LWD has the potential to actually reduce interception since storage turnover rates are lower. It is important to study LWD so it can be linked to storage to determine turnover.

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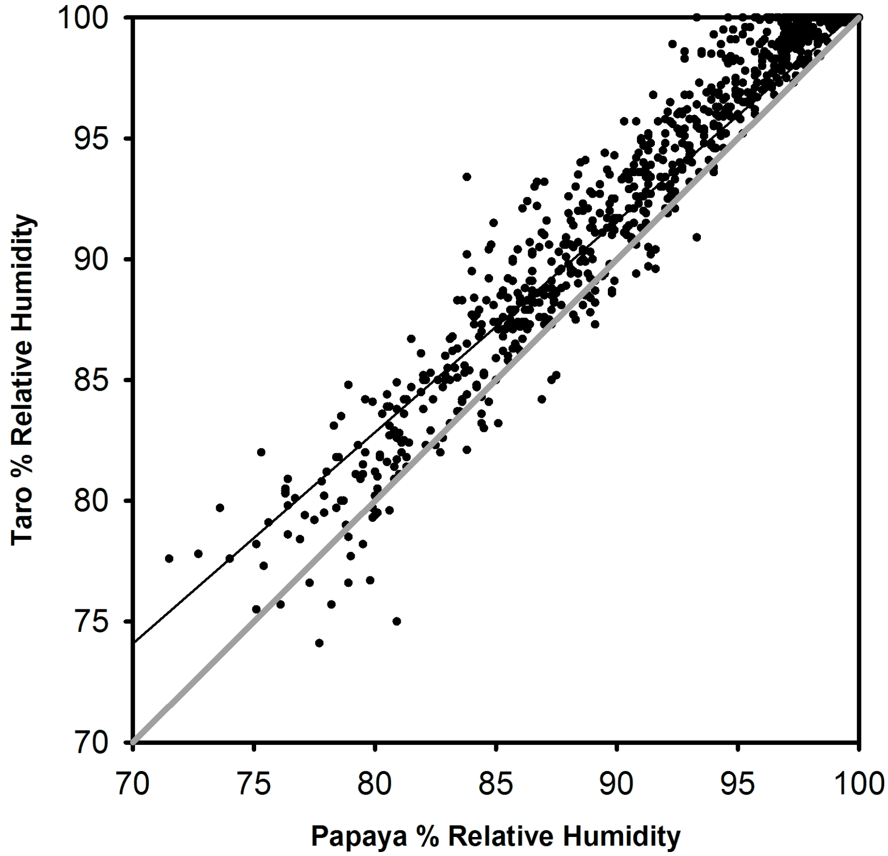
100
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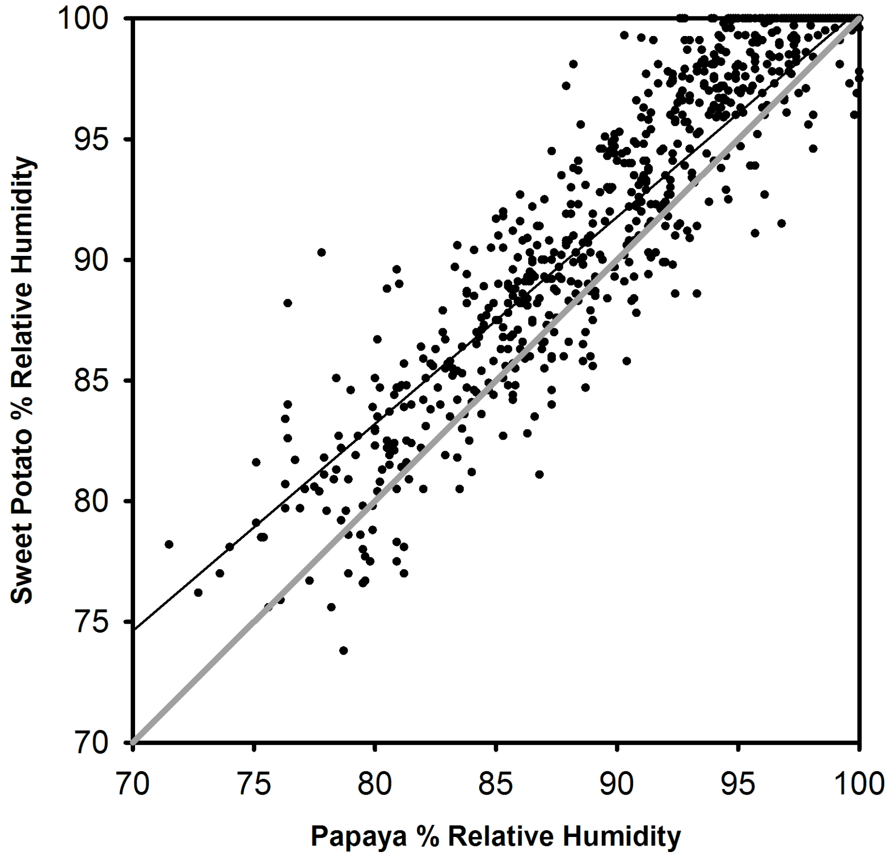
Taro % Relative Humidity
Papaya % Relative Humidity


Sweet Potato % Relative Humidity
Papaya % Relative Humidity
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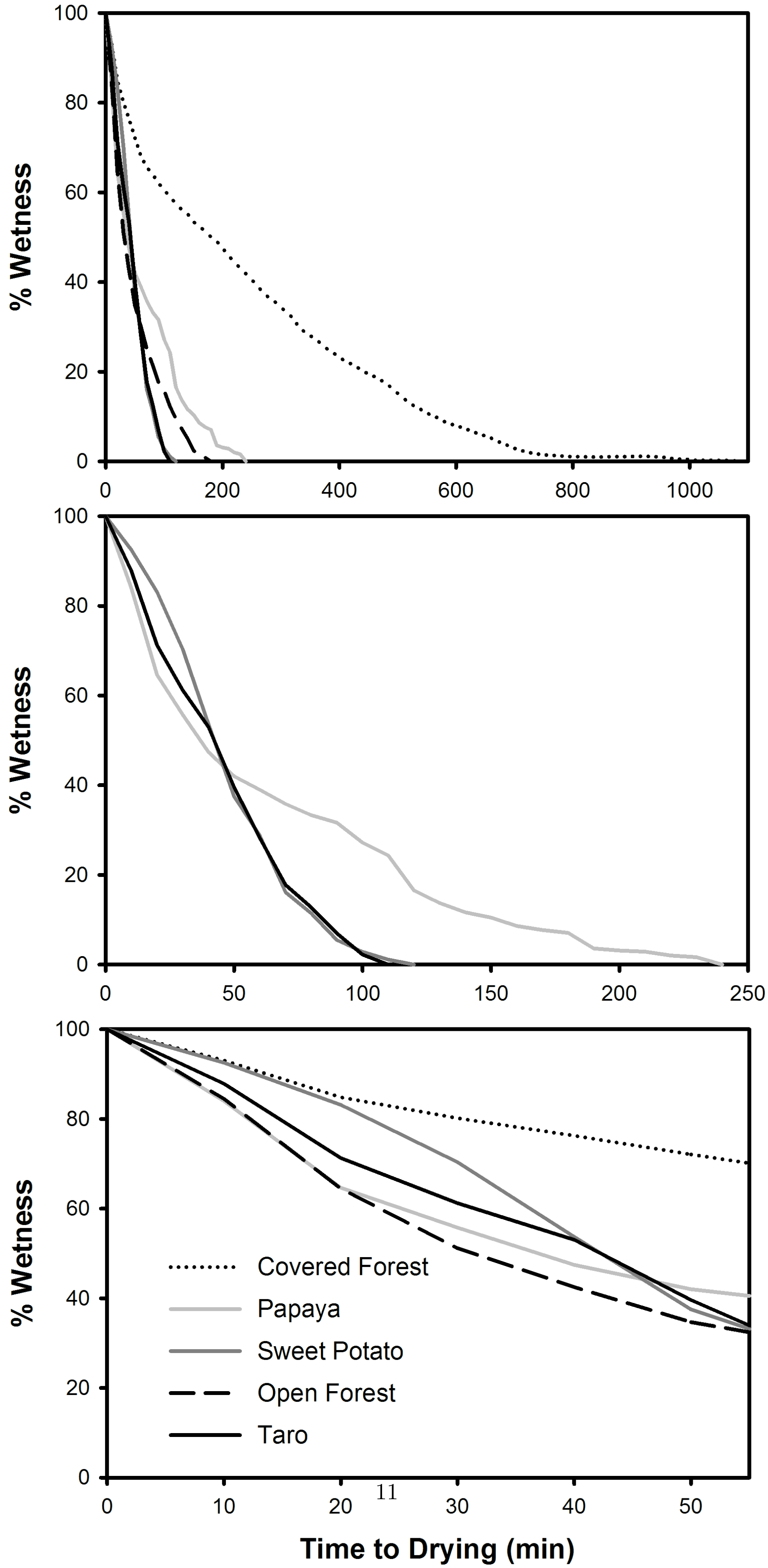
100



% Wetness
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0
0
200
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600
800
1000
% Wetness
100
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40
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50
100
150
200
250
% Wetness
100
80
60
40
20
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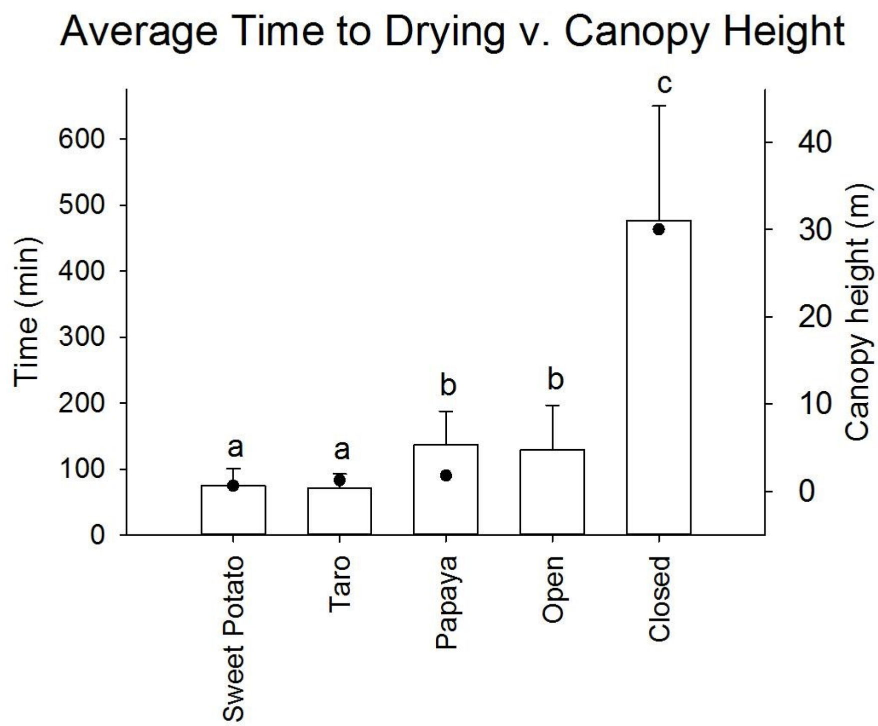
10
20
30
40
50
Covered Forest
Papaya
Sweet Potato
Open Forest
Taro
Time to Drying (min)


Average Time to Drying v. Canopy Height
Time (min)
Canopy height (m)
0
100
200
300
400
500
600
0
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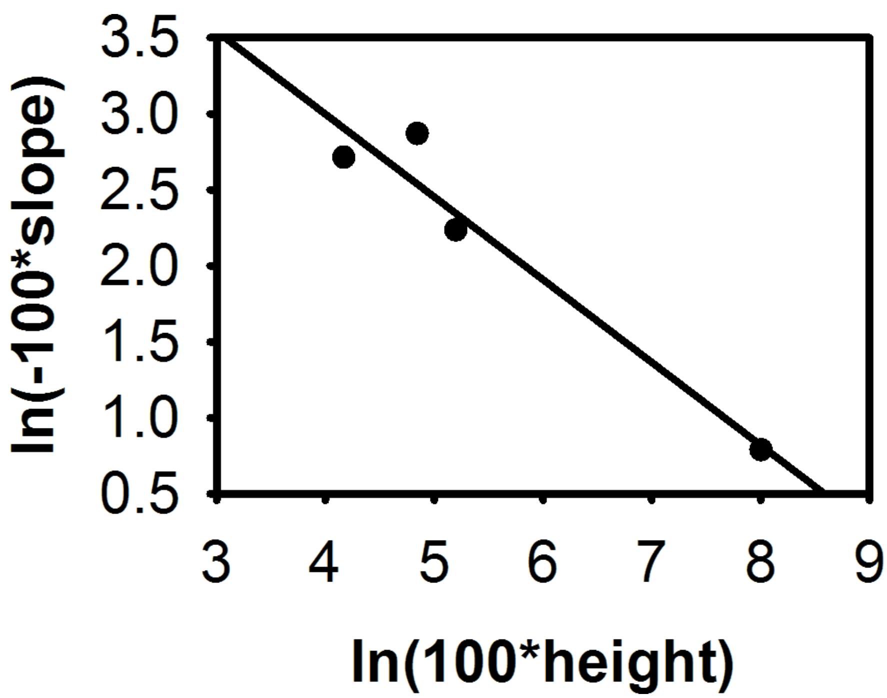
30
40
a
a
b
b
c
Sweet Potato
Taro
Papaya
Open
Closed


ln(-100*slope)
ln(100*height)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
3
4
5
6
7
8
9

Event	Day	Time of day	Papaya	Taro	Sweet Potato	Closed Forest	Open Forest
1	06/21	AM	110	90	110		
2	06/22	AM	180	100	100		
3	06/23	AM		100			
4	06/24	AM	230	70	80		
5	06/25	AM	120	60	90	250†	
6	06/26	PM	110	80	80		
7	06/27	AM			60§		
8	06/28	AM		30	80		30§
9	06/29	AM	110	80	60		170
10	06/30	PM					110
11	07/02	AM		60	60		170
12	07/03	AM[1]	180	70	60		
13	07/03	AM[2]			40		
14	07/04	AM	130	90	60		120
15	07/05	AM	60	50	40		130
16	07/07	PM					150
17	07/09	PM					240
18	07/11	PM					230
19	07/15	PM					110
20	07/17	PM					150
21	07/23	PM					180
22	07/27	PM					110
23	08/03	PM				320	
24	08/04	PM					140
25	08/08	PM					
26	09/03	PM				520	
27	09/06	PM				620	
28	09/07	AM			320		
29	09/08	AM			230		
30	09/08	PM			280		
31	09/12	PM			440		
32	09/18	PM			720		
33	09/20	PM			180		
34	09/23	AM			130		
35	09/28	PM			210		
36	10/01	PM			430		
37	10/13	PM				270	
38	10/21	PM[1]				210	
39	10/21	PM[2]				330	
40	10/24	PM				240	
41	11/01	AM				80	
42	11/01	PM				80	
43	11/04	PM				160	
44	11/07	AM			160		
44	11/07	AM			270‡		
45	11/27	AM				70	