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SHORT COMMUNICATION

The effects of precipitation regime on soil carbon pools on the Yucatan Peninsula

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Abstract: The effects of precipitation regime on the size of soil carbon (C) pools were compared in mature tropical dry forests of the Yucatan Peninsula. Our study included three forest stands in each, a dry site (potential evapotranspiration ratio = 3.2 mm mm^{-1}; mean annual precipitation = 537 mm), a wetter site (2.0 mm mm^{-1}; 993 mm) and a site in which water was comparatively less limiting (1.3 mm mm^{-1}; 1086 mm). At each site, soil C pools in dead fallen phytomass (includes leaves, flowers, fruits, small twigs and deadwood debris) deposited on the litter layer and in roots and organic matter of the mineral soil (from the upper 10 cm) were measured in samples collected during the dry season. A high proportion of the total C pool (93–95%) was in the top 10 cm of soil in all forest sites. The smallest C pool was in roots (1.8–2.4% of the total C), meanwhile the C in the litter layer represented 3–5% of the total pool. These patterns were observed irrespective of study site. However, distribution of C (i.e. wood debris vs. fine litter) varied across sites; the proportion of the forest-floor C pool in wood debris decreased from 80% in the driest site, to 51% and 42% in 993-mm and 1086-mm sites, respectively. Overall, we observed that three pools (wood debris, roots and soil organic C) provide evidence for the significant decrease in soil C storage with increase in mean annual precipitation in Yucatan Peninsula. A potential explanation for this unexpected pattern includes an increasing C turnover time with decreasing mean annual precipitation, resulting in higher C accumulation per unit of C input in the driest site.

Key Words: karst, litter layer, Mexico, roots, seasonally dry tropical forest, wood debris

Tropical forest soils contain large stocks of C (Pan *et al.* 2011), and studies and models indicate that soil C storage may be vulnerable to changes in climate conditions (Cox *et al.* 2000, Jenkinson *et al.* 1991). Knowledge of direct and indirect effects of precipitation on the C cycling and soil C storage of tropical forests has been derived from studies in mesic to wet gradients (Posadas & Schuur 2011, Schuur *et al.* 2001). Measurements on these gradients show that C storage increases with mean annual precipitation (MAP), but this trend is altered by excess precipitation. Despite seasonally dry tropical forests (SDTF) (i.e. forests with a mean annual precipitation of 250–2500 mm) occupying around 40% of the tropical forest area (Miles *et al.* 2006), and consequently their effect on the interactions between land surface and atmosphere being potentially substantial, the potential effect of precipitation variability on biogeochemical processes in these ecosystems have not been studied as extensively as in the tropical moist forests. Here, we quantify the C pools in the litter layer and in topsoil of SDTF in a regional precipitation gradient of the Yucatan Peninsula, that have the advantage that most site conditions can be assumed to be relatively similar across the gradient (e.g. mean annual temperature, topography, rock material, soil type and vegetation type).

The study was carried out in south-eastern Mexico in three sites within the Yucatan Peninsula (Chicxulub, 21°14′N, 89°32′W; X'matkuil, 20°52′N, 89°36′W; and Hobonil, 20°00′N, 89°02′W) with different precipitation regimes (Table 1). The climate is hot and subhumid and would support either tropical dry or very dry forest in the Holdridge system (Holdridge *et al.* 1971). Mean temperature across sites is around 26°C. The averages of annual precipitation (MAP) and of annual potential evapotranspiration (PET), as well as the potential evapotranspiration ratio (i.e. PET/MAP ratio),

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Table 1. General characteristics of the three study sites. Climate data from Servicio Meteorológico Nacional (personal communication), soil data from Roa-Fuentes (2013), and vegetation data from Roa-Fuentes *et al.* (2012).

	Chicxulub	X'matkuil	Hobonil
Climate			
Mean annual temperature (°C)	25.8	26.6	26.2
Mean annual precipitation (mm y^{-1})	537	993	1086
Potential evapotranspiration (mm y^{-1})	1723	2023	1457
Potential evapotranspiration ratio (mm mm^{-1})	3.21	2.04	1.34
Soil			
Bulk density (g cm^{-3})	0.70	0.78	0.91
pH	7.4	7.5	7.4
Sand (%)	74.1	64.3	57.6
Silt (%)	4.2	7.5	4.3
Clay (%)	21.7	28.2	38.1
Vegetation			
Tree density (stems ha^{-1})	2598	7210	3923
Tree height (m)	3.3	3.3	5.4
Above-ground biomass (Mg ha^{-1})	47.4	48.8	65.6

differ considerably among sites (Table 1). The landscape consists of flat areas (less than 35 m asl). Soils (lithic rendolls) are mainly shallow and organic-rich and directly overlie weathered calcium carbonate (Shang & Tiessen 2003). The predominant vegetation in the Yucatan Peninsula is SDTF in which mean canopy height is 3–5 m. Floristically, Leguminosae are the most important family in all studied sites. The whole of the Chicxulub and X'matkuil selected areas were previously used for *Agave fourcroydes* Lem. cultivation, and for slash-and-burn agriculture, whereas the Hobonil area was used for cattle ranching. All selected areas were abandoned approximately 40 y ago.

Three forest stands (5–14 km apart) were selected in each site and four plots (144 m^2) per stand were established in March 2010. Plots were installed taking into account the similar elevation and slope, and with similar MAP. In addition, plot installation was carried out avoiding large variation in the vegetation structure and composition at the local scale. In each plot, dead fallen phytomass was sampled during the dry season (March 2010) and partitioned into fine-litter fraction (includes leaves, flowers, fruits and small twigs), and deadwood debris to include all woody residues deposited on the litter layer. Fine litter was collected in four 0.5-m^2 subplots per plot. Fine-litter samples were selected to exclude all wood residues less than 5 mm in diameter. Deadwood debris was sampled using the planar-intersect technique (Kauffman *et al.* 1993), and two planar intersects were established in each plot. The diameter was measured to all pieces of wood that intersected each sample plane. A subsample of wood was taken to the laboratory to determine the specific density. Four soil cores (5 cm in diameter) from the upper 10 cm of soil (surface horizon) were collected (March 2010) randomly in each plot, combined in the field and stored at 4 °C until processing. When the soil was very shallow (< 10 cm in depth), the soil samples were collected up to rock contact. All soil samples were stored to 4 °C until they were processed. Roots in the upper soil profile (0–10 cm) were sampled using one micro-plot (1 m^2) located in a corner of each plot, which was carefully excavated.

Soil samples were hand homogenized and sieved (to pass a 2-mm mesh) in the laboratory and a subsample was dried at constant weight for moisture determination. Fine roots (2 mm or less) were separated from soil samples. The remaining soil was used to measure organic C concentrations. Roots collected from micro-plots were separated on trays, collected with forceps and classified in size classes (4 mm diameter or less; > 4 to 10 mm; > 10 to 20 mm, and > 20 mm). Samples of fine litter, and samples for each size class of wood debris and roots were oven dried at 70 °C for 48 h. A subsample of each of these samples was milled and weighed to determine C concentrations. Carbon concentrations in fine litter, wood debris, root and soils were determined using an automatic C-analyser (SHIMADZU 5000A). Soil inorganic C concentration was estimated from carbonate concentration in samples; a subsample of 5 g of each soil sample was ground, sieved (No. 100), mixed with 50 ml of 0.5 N HCl and heated until boiling over 5 min. The mixture was filtered (No. 2) and the extracts were separated to an aliquot of 5 ml. Aliquots were mixed with two drops of phenolphthalein to titrate the remaining acid with 0.25 N of NaOH (van Reeuwijk 2002). Soil organic C concentration was determined from the difference between the total C concentration and the inorganic C concentration. All analyses were performed in duplicate samples.

The mean of each C pool was calculated for each forest stand, and these means were averaged to obtain the regional values. The resulting C masses in each pool, including three stands in each site, were analysed by

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Table 2. Soil carbon pools in three study sites of Yucatan Peninsula. Data are mean ± SE of three forest stands. Different lowercase letters (a, b) indicate means are significantly different, when testing for differences among regions. NS, P ≥ 0.05; *, P < 0.05; **, P < 0.01.

	($Mg\ C\ ha^{-1}$)			
Pool	Chicxulub	X'matkuil	Hobonil	$F_{2,6}$
Fine litter	1.04 ± 0.03b	1.55 ± 0.21a	1.77 ± 0.22a	7.83*
Wood debris				
Diameter (mm)				
≥ 5–25	1.75 ± 0.28a	0.95 ± 0.08b	0.48 ± 0.19c	10.3*
> 25–76	1.90 ± 0.19a	0.63 ± 0.03b	0.61 ± 0.28b	13.7**
> 76	0.37 ± 0.19a	0.05 ± 0.02a	0.19 ± 0.10a	1.67 NS
Total	4.02 ± 0.69a	1.63 ± 0.17b	1.28 ± 0.59b	10.5*
Roots to 10 cm				
Diameter (mm)				
≤ 4	1.58 ± 0.12a	0.98 ± 0.11b	0.73 ± 0.08b	11.8**
> 4–10	0.92 ± 0.14a	0.45 ± 0.05b	0.31 ± 0.04c	15.7**
> 10–20	0.51 ± 0.08a	0.32 ± 0.04b	0.24 ± 0.01b	6.17*
> 20	0.07 ± 0.03a	0.11 ± 0.01a	0.13 ± 0.02a	1.01 NS
Total	3.08 ± 0.38a	1.86 ± 0.22b	1.41 ± 0.15b	16.2**
Soil to 10 cm	123 ± 7.0a	97.8 ± 9.9b	59.3 ± 4.8c	21.2**
Total	131 ± 6.4a	103 ± 10.6b	63.8 ± 6.2c	20.3**

one-way ANOVA. Thus, analysis of variance was based on three sites, each them included three forest stands. The honest significant difference (HSD) test was used to examine the effect of site on C pools on the litter layer, soil and roots. Where necessary, data were log-transformed. Statistical analyses were performed using R 2.13.1 1 (http://www.rproject.org).

Fine-litter C pool increased with increasing MAP (Table 2). In contrast, C pools in total wood debris decreased with increase in MAP, reflecting large differences across sites in pools associated with lower size classes. Also C pools in total root biomass were larger in the driest, Chicxulub site, than in wetter sites (by a factor of 1.7 relative to C pools in X'matkuil, and by a factor of 2 relative those pools in Hobonil). Differences across sites reflected changes in C pools for size classes lower than 20 mm in diameter. Roots of the largest size class (i.e. > 20 mm in diameter) constituted a statistically homogeneous group across sites (P > 0.05). Chicxulub soils also had the highest organic C pools relative to soils from wetter counterparts. Overall, we found a decreasing gradient in the total C pool in Yucatan soils in the direction of Chicxulub > X'matkuil > Hobonil, and the corresponding ANOVA indicated that this gradient is highly significant.

A high proportion of the total C pool (93–95%) was in the top 10 cm of soil in all forest sites. The smallest C pool was in roots (1.8–2.4% of the total C), meanwhile the C in the litter layer represented 3–5% of the total pool. These patterns were observed irrespective of study site. However, distribution of C in the litter layer (i.e. wood debris vs. fine litter) varied across sites; the proportion of the forest-floor C pool in wood debris decreased from 80% in the driest site, to 51% and 42% in X'matkuil and Hobonil sites, respectively.

Total C pools on the Yucatan Peninsula, calculated from Table 1 (for above-ground biomass with a C concentration of 50%; 23.7 Mg C ha^{-1} for Chicxulub, 24.4 Mg C ha^{-1} for X'matkuil and 32.8 Mg C ha^{-1} for Hobonil) and Table 2, were 154 Mg C ha^{-1} for Chicxulub, 127 Mg C ha^{-1} for X'matkuil and 96.6 Mg C ha^{-1} for Hobonil. Surface-soil C accounted for 85%, 81% and 66% of the total C for Chicxulub, X'matkuil and Hobonil sites, respectively. These C proportions in Yucatan soils are larger than values in other tropical forest soils (soil C accounted for 32% of total C in tropical forests; De Deyn *et al.* 2008, Pan *et al.* 2011). Our data are not enough to support a mechanistic explanation. However it has been reported that karstic soils and specifically Yucatan's soils have high potential to form aggregates with carbonates, favouring C stabilization by slow organic matter decomposition (Shang & Tiessen 2003). Thus, the stabilization of the C and the low water availability in Yucatan's soils driving a low metabolic activity prevent C losses by either soil respiration or leaching.

Three pools provide evidence for the significant decrease in soil C storage with increase in MAP in Yucatan Peninsula (wood debris, roots and soil organic C). The consistent trend with precipitation amount in soil C storage that we found seems to contradict findings that C storage in tropical forest soils increases with MAP (Posadas & Schuur 2011, Schuur *et al.* 2001). A potential explanation for this inconsistency between our and Schuur's studies includes an increasing C turnover time with decreasing MAP, resulting in higher C accumulation per unit of C input in the driest site. Inter-site experiments conducted throughout the tropics show that rainfall is positively correlated with decay rates in tropical forests (Powers *et al.* 2009). Decomposition rates of leaves from

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dominant tree species were measured across the local precipitation gradient in Yucatan where other factors (topography, parent material, vegetation and ecosystem age) were held constant (M. Bejarano unpubl. data). Results of these experiments indicate that decomposition rates of leaves placed on the soil surface increase by 55% with increased precipitation, whereas litterfall increased only by 10% across the gradient (J. Campo pers. obs.). Thus, decomposition processes may be inhibited to a greater degree than plant productivity at low levels of precipitation, and lead to an accumulation of soil organic matter.

The new climate relationships observed in the Yucatan Peninsula add to our conceptual understanding of the effect of precipitation regime on soil carbon storage in tropical forests. Patterns observed in carbon storage in Yucatan soils have several implications for how carbon sequestration and turnover in tropical forests may respond to climate change.

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