Modeling the Effects of Throughfall Reduction on Soil Water Content

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ABSTRACT

Access to water reserves in deep soil during drought periods determines whether or not the tropical moist forests of Amazonia will be buffered from the deleterious effects of water deficits. Changing climatic conditions are predicted to increase periods of drought in Amazonian forests and may lead to increased tree mortality, changes in forest composition, or greater susceptibility to fire. A throughfall reduction experiment has been established in the Tapajós National Forest of east-central Amazonia (Brazil) to test the potential effects of severe water stress during prolonged droughts.

The objective of this component of the throughfall reduction study is to develop an understanding of the physical processes driving the observed soil-water dynamics at the site.

Using Time-Domain Reflectometry observations of water contents from this experiment we have developed a dynamic, one-dimensional, vertical flow model to elucidate our understanding of hydrologic processes within these tall-stature forests on well-drained, upland, deep Oxisols and to simulate changes in the distribution of soil water.

Simulations using 3-yrs of data accurately captured mild soil-water depletion near the surface after the first treatment year and decreasing soil moisture at depth during the second treatment year. The model is sensitive to the water retention and unsaturated flow equation parameters, specifically the van Genuchten parameters θs, θr, and n, but less sensitive to Ks and α.

The low root-mean-square-error between observed and predicted volumetric soil water content suggests that this vertical flow model captures the most important hydrologic processes in the upper-landscape position of this study site. The model indicates that rates of evapotranspiration within the exclusion plot have been sustained at the expense of soil water storage.

THE EXPERIMENT

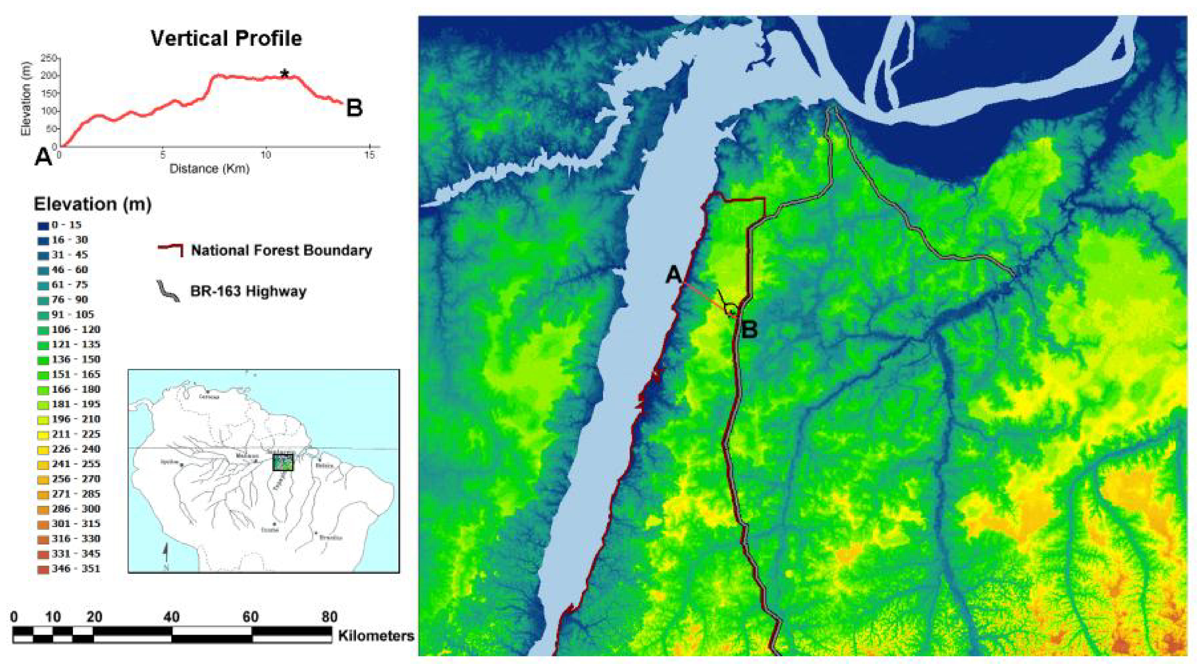


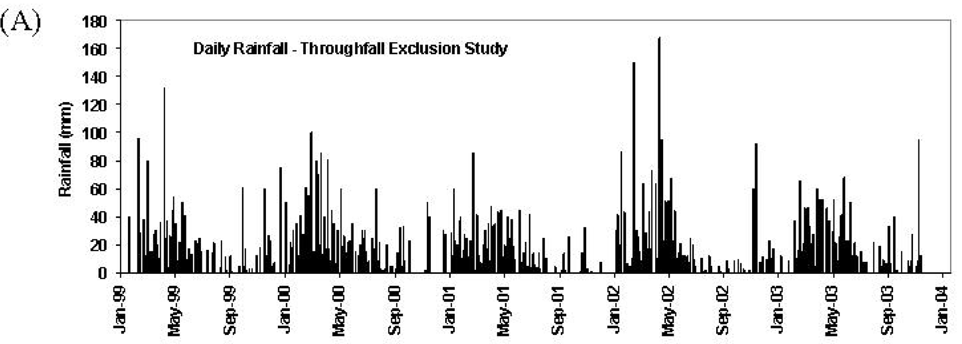
Figure 1. The study site is located in the Tapajos National Forest at km 67 outside the city of Santarem, Brazil. The study plots are approximately 150 m above and 13 km east of the Tapajos River. The study plots are situated on a relatively level, upper-landscape plateau position where the soils are predominantly Haplustox (Latasolos vermelhos) dominated by kaolinite clays, and support a terra firme forest. The figure demonstrates that similar landscape conditions are common in the region.

Figure 2: The throughfall reduction experiment was initiated in 1998. The experiment compares two one-hectare plots, one of which receives natural rainfall, while the other has plastic panels installed in the forest understory during the rainy season. These panels capture approximately sixty percent of incoming throughfall. After a one-year pretreatment period, plastic panels were installed at the beginning of the 2000 rainy season that extends from January to May. Panels are removed during the dry season and re-installed prior to the rainy season of the following year. A variety of processes are being monitored, including: tree growth and mortality, sapflow, litterfall, leaf area index, forest floor decomposition, soil respiration, trace gas emissions, forest floor flammability, and the amounts and chemistry of precipitation, throughfall, litter leachate, and soil solutions.

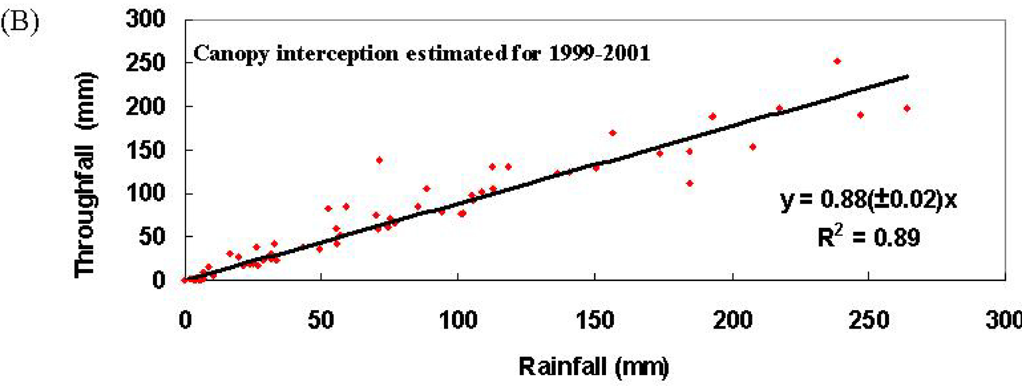
MODEL STRUCTURE AND INPUTS

The model was designed to simulate daily changes in the distribution of soil water. Rainfall inputs (A), canopy interception (B), and throughfall exclusion (C) determine water flux to the soil surface. Vertical water movement through 13 soil layers (D) is driven by the soil water content (E1), the difference in total soil hydraulic head (E2), wich integrates the effect of matric (F) and gravitational forces (E3), and unsaturated hydraulic conductivity (E4) that is estimated from measured saturated hydraulic conductivity (G). Changes in soil water storage are then modeled (E5) including plant uptake of water by the forest vegetation as an outflow (E6), which is driven by potential evapotranspiration and fine root distribution (H). Input variables and units are defined in Table 1. Simulations were performed for the control plot with no reduction in water inputs and for the treatment plot using throughfall exclusion during the rainy season. Model predictions were compared to time domain reflectometry measures (I). The soil moisture measurements alone would not be sufficient to describe the rates of water fluxes because two soil layers may contain the same water volume within a given soil volume, but have different rates of fluid movement through them. This means that model estimations of water fluxes are required in order to fully quantify the hydrologic system.

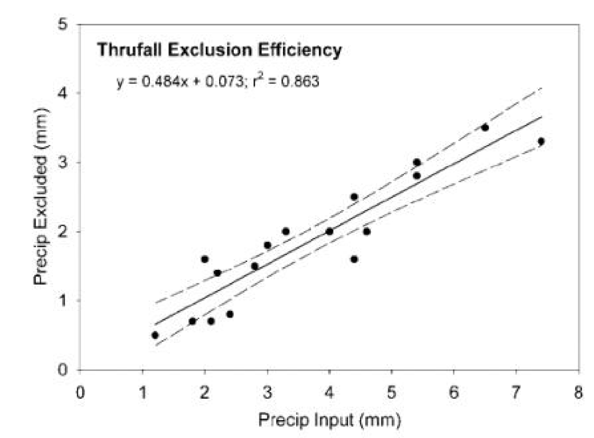
(A)



(B)



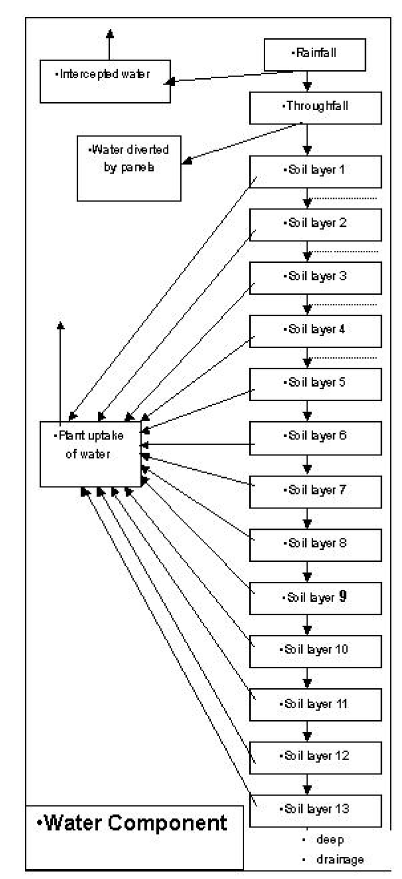
(C)



E6: $U(z) = U_{max} R(z) URF(z)$

Plant Uptake is a function of maximum soil water uptake (U_{max}) partitioned by root density for a given soil layer ($R_{(z)}$) and limited by the matric head in that soil layer ($URF_{(z)}$)

(D)



E1: $\theta(z) = \frac{D_w(z)}{\Delta z}$

Soil water content (θ) is determined for each soil layer using water depth (D) and layer thickness (Δz).

E2: $q_z = K(\theta)\frac{\Delta H}{\Delta z}$

Water flux between soil layers is determined using Darcy's law for one-dimensional (vertical), unsaturated flow where qz is the vertical water flux (m s-1), K(θ) is the unsaturated hydraulic conductivity (m s-1), ΔH is the difference in total hydraulic head between two adjoining layers (m) and Δz is the downward-directed, vertical distance between the midpoints of the layers (m).

E3: $h_m = \frac{1}{\alpha}[\Theta^{-1/m} - 1]^{1/n}$

The matric head of the soil water is determined by the van Genuchten equation relating water content to matric head where Θ=(θ-θr)/(θs-θr) with s and r being saturated and residual water content.

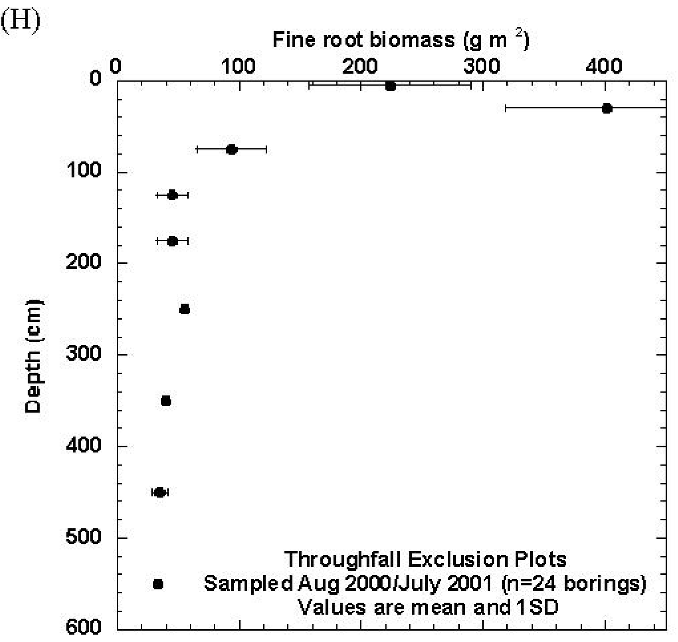
E4: $K(\theta) = K_s \Theta^{1/2}\left[1 - [1 - \Theta^{n/(n-1)}]^m\right]^2$

Unsaturated hydraulic conductivity, K(θ), is calculated from saturated hydraulic conductivity, Ks, according to the equation of Mualem (see (G)).

E5: $\frac{\partial q_z(z)}{\partial z} \pm U(z) = \frac{\partial \theta(z)}{\partial t}$

Changes in soil water storage are modeled using the Richards' (mass balance) equation that accounts for inflows and outflows in each layer. Root uptake is the main mechanism for water loss (see (E6) and (H)).

(H)

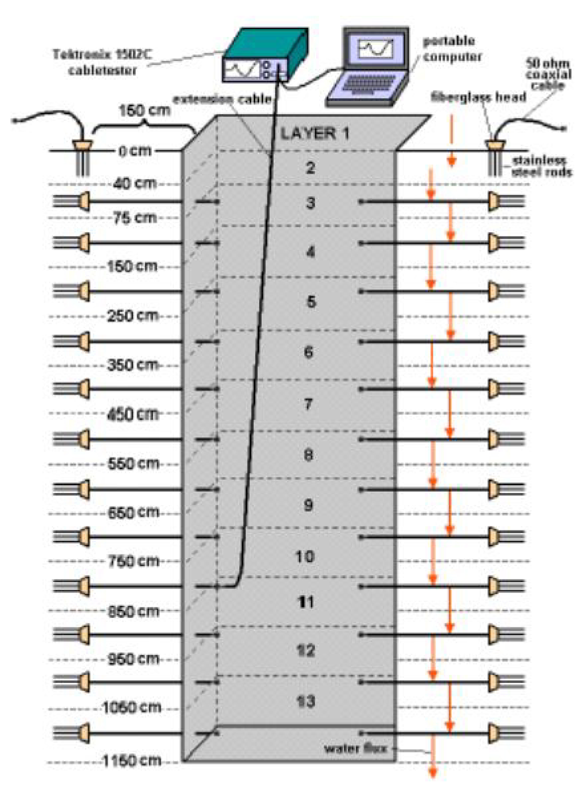


The fraction of the total fine (live) root biomass (0-2 mm) in each layer was used to estimate a rooting factor, R(z), for each modeled soil layer.

Table1: Model inputs. Parameters with (z) are input for each layer of soil.

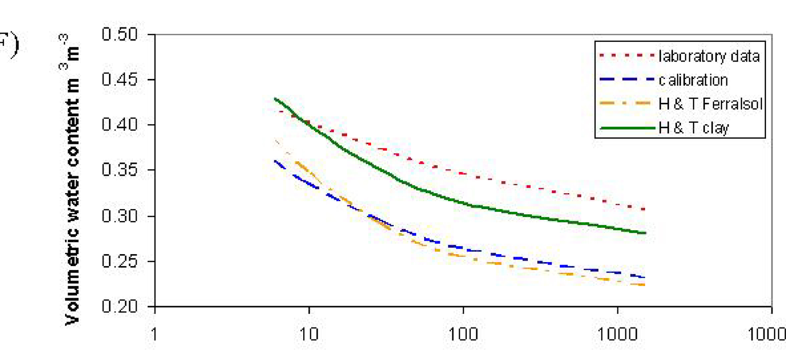
Input	Description	Units
Rainfall	Daily rainfall depth	$mm\,d^{-1}$
PET	Daily potential evapotranspiration	$mm\,d^{-1}$
Throughfall	Rainfall entering soil surface	fraction
Δz(z)	Distance betweem layers	m
H(z)	Total hydraulic head	m
D_w(z)	Water depth in soil layer	m
K_s(z)	Saturated hydraulic conductivity	$m\,s^{-1}$
R(z)	Root length or biomass present	fraction
Van Genuchten Parameters:		
θ_s(z)	saturated water content	$m_w^3\,m_s^{-3}$
θ_r(z)	residual water content	$m_w^3\,m_s^{-3}$
α(z)	water retention	m^{-1}
n(z)	water retention	-

(I)



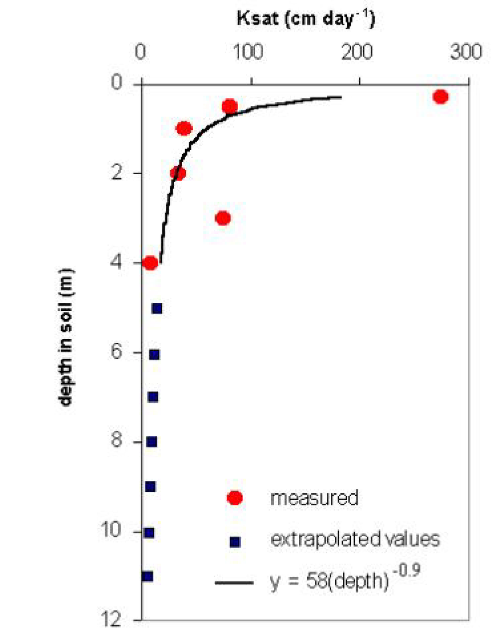
Volumetric water contents ($m^3\,m^{-3}$) were measured using Time Domain Reflectometry (TDR) approximately once per month.

(F)



Soil water retention data were generated by a standard pressure plate method and data were fit to van Genuchten soil moisture characteristic functions using nonlinear regression. Curve of Hodnett and Tomasella (H&T) were used for comparison..

(G)



Saturated hydraulic conductivity (Ks) was quantified from 0-4 m using a Guelph permeameter (n=7 bore holes. Values below 4 m were estimated.

MODEL OUTPUTS

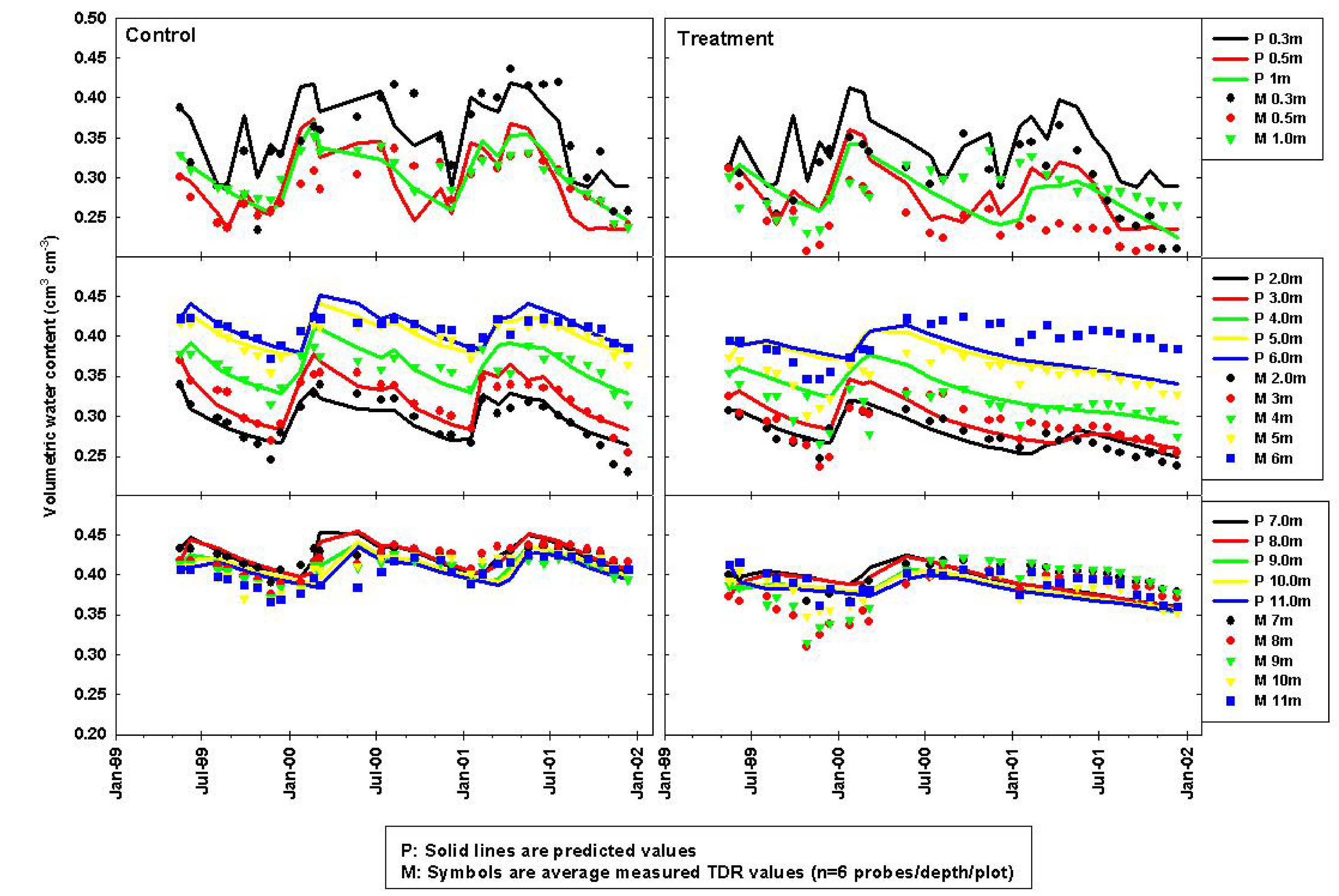


Figure 3: Model calibrations with control plot data resulted in a Root Mean Square Error (RMSE) between the measured and predicted volumetric water content for all depths of 1.88 percent water content, which is a Relative RMSE of 5.1 percent. The top two layers have poorer fits than the others, with RRMSEs of 10 percent or greater. The errors in the other horizons are all below 5.4 percent. The calibrated model succeeds in capturing important seasonal trends and shows the expected delay in recharge and depletion responses with increasing depth.

Using the control plot calibration the modeled soil water content in the throughfall-exclusion plot had a RMSE in soil moisture of 3.1 percent water content. This is a RRMSE of 9.2 percent. The mean difference is -0.65±0.16 percent water content. Overall, the treatment plot simulation model was able to explain about 73 percent of the variability in the volumetric water content data (see Figure 4). The model over-predicts lower TDR readings and slightly under-predicts the wetter ones. Additionally, from 6-11 m the model simulates a greater drawdown of water than the TDR data indicate, especially during the second post-treatment rainy season.

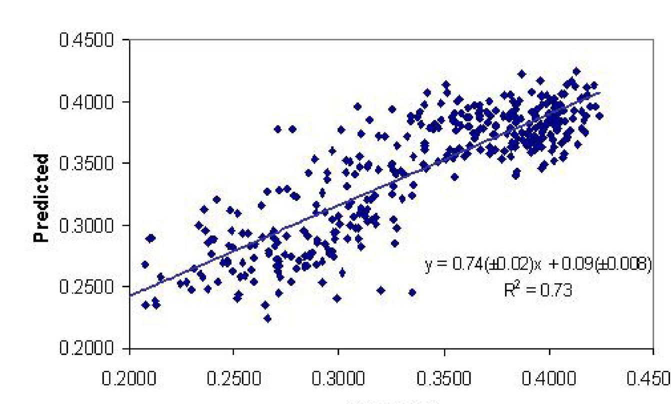


Figure 4. Correlation between measured and predicted volumetric water contents (VWC) in the treatment plot. The comparison is for 29 dates between May 1999 and December 2001 on which VWC was measured at the field site.

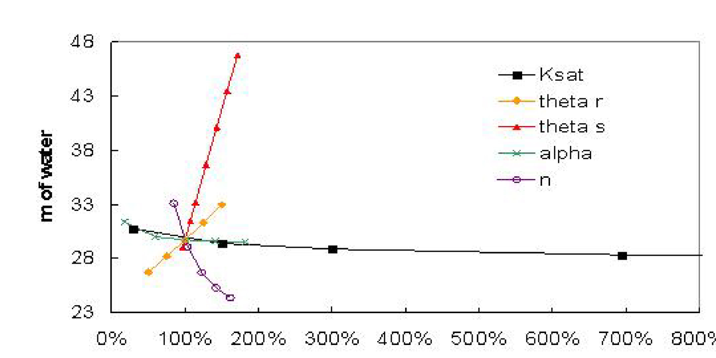


Figure 5. Sensitivity analysis of θ_s, θ_r, α, n and K_{sat} for 1.5-2.5 m showing the effect of a change in the parameter values on the average depth of water in that layer over the simulation period. The analysis demonstrates a greater sensitivity (steeper slope) to the van Genuchten parameters θs, θr, α, n than to K_{sat}.

Table 2: Over the simulation period, the fraction of water lost to deep drainage is smaller under the treatment. In the control plot, about 45 percent of water input to the soil is drained past 11.5 m, compared to 17 percent in the treatment plot. The slower rates of water flow and lower steady water fluxes in the treatment plot are due to lower water content (more negative matric heads) in the soil layers. Note, however, the evapotranspiration is similar for the two plots.

	Control	Treatment
	----- m year^{-1} -----	
Rainfall	1.93	1.93
Interception	0.23	0.23
Exclusion	0	0.66
Throughfall	1.69	1.04
Evapotranspiration	1.35	1.30
Flux past soil depth:		
0.4 m	1.02	0.38
0.75 m	0.90	0.28
1.5 m	0.86	0.23
2.5 m	0.84	0.21
3.5 m	0.84	0.20
4.5 m	0.83	0.20
5.5 m	0.82	0.19
6.5 m	0.81	0.18
7.5 m	0.80	0.18
8.5 m	0.79	0.16
9.5 m	0.78	0.16
10.5 m	0.77	0.16
11.5 m	0.77	0.18
Δ Water storage	-0.20	-0.21

Conclusions:

The one-dimensional model used in this study predicts soil volumetric water content within three percent of water content measures obtained using TDR probes in six 11-m deep soil shafts for the three years of the throughfall reduction experiment. This accuracy of prediction indicates that physical processes of soil-water movement in the ecosystem are captured by the model even despite the relatively coarse vertical and temporal scale of modeling. Landscapes with more complex terrain may require models with additional dimensions, but one-dimensional, vertical flow seems appropriate fore well-drained plateau sites - a common feature of the Amazon basin.