A Pedotransfer Resource Database ($P_{TF}RD_B$) for tropical soils: test with the water balance of WaNuLCAS

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Abstract Dynamic models of the soil-plant-atmosphere continuum can help to clarify relationships between land use and water resources, provided that they are correctly parameterized. The WaNuLCAS model for Water, Nutrient, and Light Capture in Agroforestry Systems was developed for such tasks in tropical conditions. However, the field measurements required for full model parameterization are laborious, costly and time consuming, so shortcuts are desirable. Pedo transfer functions (PTF) have been developed to predict the main soil physical relationships (θ-h-K) from the measured percentages of clay, silt, organic matter content, and bulk density. However, existing equations are largely based on temperate soils and as they are empirical, rather than based on first principles, these PTF's may gave erroneous, or even completely absurd predictions when used outside the range of soils from whose data they were derived. Even so, complete textural data are not easily obtained, and as a further step, these data themselves may be derived from soil classification data and manually assessed texture classes. A new database, $P_{TF}RD_B$, of input parameters for PTF's was collected and summarized from 8915 data available worldwide, with good representation of tropical soils. When the resultant estimates are used as basis for θ-h-K relationships, the results of the $P_{TF}RD_B$ appeared close to those derived from field measurements. The largest deviations occurred on vertisols and mollisols, where bulk density and soil organic matter content diverged. When further tested in the WaNuLCAS model for a 10-year simulation of a simple agroforestry system, differences between soil types were simulated consistently, although on various soil types one or more of the processes of the water balance appeared to vary with the way input parameters were derived. For crop yields, tree wood production and cumulative water balance terms, however, these impacts were small, with the largest consistent difference in the partitioning between surface runoff and vertical drainage on the vertisol.

Keywords: *Agroforestry; Data-base; Pedotransfer; Soil Texture; Tropics; WaNuLCAS; water-balance*

1 INTRODUCTION

With the increasing interest in the relationship between land use, land degradation and water resources, research tools initially developed for sites with intensive data collection need to be applied more widely, often in situations where only coarse-resolution data exist for use as model inputs. 'Pedo transfer' functions (PTF's) allow the estimation of parameters that describe detailed dynamic behaviour of soils on the basis of more easily measured or observed properties (Rawls et al., 1991; Van den Berg et al., 1997); Wösten *et al.*, 1998). A key question is how much impact the use of such derived estimates, rather than directly measured values, have on overall model outcomes, given the various feedbacks in such models. We describe a test of soil physical pedo transfer functions based on soil texture, used in the tree-soil-crop interaction model WaNuLCAS (Van Noordwijk and Lusiana, 1999, 2000) that can be used to estimate the water balance of agroforestry systems in the context of 'watershed functions'.

Soil water balance models generally require relationships in the triangle of volumetric soil water content (θ), pressure head (h) and hydraulic conductivity (K). An effective, generic approach can be found in the hydraulic equations of van Genuchten (1980). A set of continuous PTF's for the parameters of this equation was developed by Wösten *et al.* (1998) on the basis of more easily observed parameters such as texture and bulk density. However, there is a risk that the PTF's may give erroneous, or even completely absurd predictions when the models are used outside the range of soils from which data were derived (Hodnett, 2000). Data sets underlying these functions largely consist of temperate soils, while data collected for tropical soils have not been systematically evaluated in this context.

Therefore, the objective of this paper is to (1) present a new database, $P_{TF}RD_B$, for the main tropical soil taxonomic, textural and hydrological classes, (2) to test the PTF's of $P_{TF}RD_B$ in simulations to predict θ-h-K in tropical soils against actual field measurements, and (3) to test the $P_{TF}RD_B$ with actual field measurement as input against the generic single PTF in the context of WaNuLCAS simulations of the water balance of a simple agroforestry system.

Table 1. Continuous PTF's for the parameters of the van Genuchten equations for prediction of θ-h-K relationships in temperate soils of the Netherlands and UK (after Wösten *et al.*, 1998).

$$\theta s = 0.7919 + 0.00169*Cl - 0.29619*BD - 0.00000149\ Si^2 + 0.0000821\ OM^2 + 0.02427/Cl + 0.01113/Si + 0.01472*\mathrm{Ln}(Si) - 0.0000733*OM*Cl - 0.000619*BD*Cl - 0.001183*BD*OM - 0.0001664*TS*Si$$

$$Ks = \mathrm{Exp}.(7.755 + 0.0352*Si + 0.93*TS - 0.967*BD^2 - 0.000484*Cl^2 - 0.000322*Si^2 + 0.001/Si - 0.0748/0M - 0.643*\mathrm{Ln}(Si) - 0.01398*BD*Cl - 0.1673*BD*OM + 0.02986*TS*Cl - 0.03305*TS*Si)$$

$$\alpha = \mathrm{Exp}.(-14.96 + 0.03135*Cl + 0.0351*Si + 0.646*OM + 15.29*BD - 0.192*TS - 4.671*BD^2 - 0.000781Cl^2 - 0.00687*OM^2 + 0.0449/OM + 0.0663*\mathrm{Ln}(Si) + 0.1482*\mathrm{Ln}(OM) - 0.04546*BD*Si - 0.4852*BD*OM + 0.00673*TS*Cl)$$

$$\lambda = ((10*(\mathrm{Exp}(0.0202 + 0.0006193*Cl^2 - 0.001136*OM^2 - 0.2316*\mathrm{Ln}(OM - 0.03544*BD*Cl + 0.00283*BD*Si + 0.0488*BD*OM))) - 10) / (1 + (\mathrm{Exp}((0.0202 + 0.0006193*Cl^2 - 0.001136*OM^2 - 0.2316*\mathrm{Ln}(OM - 0.03544*BD*Cl + 0.00283*BD*Si + 0.0488*BD*OM)))$$

$$n = \mathrm{Exp}(-25.23 - 0.02195*Cl + 0.0074*Cl - 0.194*OM + 45.5*BD - 7.24*BD^2 + 0.0003658*Cl^2 + 0.002885*OM^2 - 12.81/BD - 0.1524/Si - 0.01958/OM - 0.2876*\mathrm{Ln}(Si) - 0.0709*\mathrm{Ln}(OM) - 44.6*\mathrm{Ln}(BD) - 0.02264*BD*Cl + 0.0896*BD*OM + 0.00718*TS*Cl)) + 1$$

with an additional option to estimate BD from texture and organic matter content:

$$BD = 1/(-1.984+0.01841*OM+0.032*TS+0.00003576*(Cl+Sl)^2+67.5/MPS+0.424*\mathrm{LN}(MPS)) \text{ if } ((Cl+Sl)<50, \text{ else } BD = 1/(0.603+0.003975*Cl+0.00207*OM^2 +0.01781*\mathrm{LN}(OM))$$

Cl is percent clay (i.e. percent < 2 μm); *Sl* is percent silt (i.e. percent 2 μm< *Cl* < 50 μm); *OM* is percent organic matter; *BD* is bulk density (g cm^{-3}); *TS* is a switch, with a value of 1 for topsoil and 0 for subsoil; LN is the natural logarithm; *MPS* = mean particle size of sand (default 290 μm)

2 PEDOTRANSFER FUNCTIONS

When evaluated in a relevant range of input parameters, the pedotransfer function (Table 1) suggests that the effect of soil organic matter content on θ-h-K is relatively small and mainly exists in relatively dry soils, if evaluated at constant bulk density. Bulk density, if evaluated for the same organic matter content, has the opposite effect on the θ-h-K relationship compared to soil organic matter. Bulk density exerts a strong influence in wet soils (for $\theta < 0.3$ m^3 m^{-3}) increasing θ at low pF (pF equals $^{10}\log(-h)$). When bulk density decreases, the water retention below pF 3 increases and hence the capacity of soil to retain water available for crops increases. Bulk density is a reflection of soil structure, and the main effect of organic matter on water retention is probably through its relation to structure and thus bulk density, rather than direct. Given the large impact bulk density on the θ-h-K relationship, particularly at higher soil moisture, it appears necessary to use measured values of bulk density for each simulated land use system for the PTF's in the investigated soil.

3 PEDOTRANSFER RESOURCE DATABASE ($P_{TF}RD_B$): INPUT DATA FOR MODELLING PURPOSE

A new database was constructed, by combining a databases developed previously by Hodnett (2000) (that originated from two databases, WISE and IGBP-DIS), from Oak Ridge National Laboratory, Distributed Active Archive Center (ORNL DAAC), from The Woods Hole Research Center (WHRC) and from soil taxonomy (USDA, 1975). Additional soil data were obtained from the Indonesian-soil database developed at the Center for Soil Agro climate Research, Bogor, and some unpublished research available in Soil Science Departments of Brawijaya University Malang), Gajah Mada University (Yogyakarta) and Bogor Agricultural University (IPB). Input parameters for the Wösten PTF's (measured percentages of clay, silt, organic matter content, and bulk density) was thus collected and summarized from 8915 data available worldwide. This data can cover information for eleven main tropical soil taxonomic orders and twelve soil textural classes from 24 tropical countries.

Table 2. Comparison of outputs of $P_{TF}RD_B$ (DB) with actual field measurements (FM) for the same soil layers.

Soil Tick-ness (cm)	Clay (%)		Silt (%)		OM (%)		BD (%)	
	DB	FM	DB	FM	DB	FM	DB	FM
A. Soil Type: Vertisol; Location: Sumberejo, Blitar, East Java								
14	59	60	25	17	1.81	1.29	1.30	1.69
17	65	70	22	16	1.20	0.72	1.32	1.55
31	62	70	24	15	0.97	0.52	1.40	1.55
32	65	57	22	24	0.58	0.38	1.40	1.52
66	65	57	20	17	0.47	0.31	1.48	1.54
B. Soil Type: Inceptisol Location: Bodong, Sumberjaya, West Lampung								
20	57	63	28	29	2.18	2.19	1.08	1.07
33	60	68	27	24	1.72	1.31	1.16	1.13
20	59	67	26	24	1.10	1.12	1.19	1.16
27	60	67	26	24	0.92	1.10	1.19	1.15
C. Soil Type: Alfisols; Loc.: Punjul, Tulungagung, East Java								
18	34	24	11	12	1.83	0.81	1.24	1.07
29	58	45	25	20	1.52	0.84	1.20	1.31
26	58	43	26	21	-	0.34	1.22	1.19
19	55	45	25	22	0.77	0.29	1.39	1.27
16	35	35	29	25	0.45	0.41	1.32	1.26
30	54	41	25	28	0.41	0.38	1.36	1.25
20	55	43	22	29	0.31	0.38	1.34	1.25
D. Soil Type: Mollisol; Location: Tlogorejo, Malang, East Java								
16	14	12	29	32	1.56	1.21	1.02	1.49
31	20	17	41	49	1.78	1.52	1.24	1.39
21	20	16	41	47	1.08	1.14	0.97	1.27
23	20	21	44	46	0.50	0.97	1.30	1.29
19	13	7	28	39	0.77	0.86	1.20	1.24
40	-	19	-	42	-	0.64	-	-
25	-	19	-	54	-	0.79	-	-
E. Soil Type: Ultisol; Location: Pakuan Ratu, North Lampung								
5	13	15	18	12	1.86	2.79	1.26	1.36
12	26	26	16	14	1.27	1.29	1.42	1.39
29	26	28	15	15	0.75	0.83	1.51	1.52
41	27	34	15	15	0.54	0.43	1.54	1.52
25	56	42	22	16	0.65	0.14	1.27	1.55
38	55	64	24	15	0.59	0.14	1.34	1.50
F. Soil Type: Entisol, Location: Dadapan, Malang, East Java								
18	6	3	14	22	1.74	2.50	1.17	-
26	7	1	11	19	0.87	0.80	1.23	-
24	7	1	10	15	0.53	0.55	1.16	-
25	5	2	4	12	0.24	0.40	1.60	-
21	7	3	10	11	0.53	0.40	0.96	-
46	-	4	-	17	0.25	0.35	0.94	-

As alternative to the use of measured data on soil texture, $P_{TF}RD_B$ also allows for the use of field soil texture classes as derived from manually handling ("feeling") each soil horizon, with soil type determined by soil morphological description or from soil map information. Based on the input parameter, the $P_{TF}RD_B$ will supply the clay, silt and soil organic matter (OM) content, and soil bulk density (BD) for each soil depth as input for PTF's (Table 2). Field data measurements for the same soils in Table 4 indicate that soil texture is fairly well represented in the estimation method, but that in organic matter and bulk density estimates a considerable deviation error may be introduced, especially in the top layer of the vertisol and mollisol in the example. This error in the inputs to the soil physical PTF may be further enhanced in the next steps of the calculation.

The θ-h-K relationships derived from $P_{TF}RD_B$ estimates on the basis of soil textural classes where compared to those obtained from actual field measurement of texture, bulk density and organic matter content as input for the Wösten PTF's, using data from the top four layers in Table 2 of the six soil types. The comparison of the θ-h relationships is presented as paired θ data at different h (Figure 1). The θ-K relationships showed good agreement, with a R^2 of over 0.96-0.99 and a slope of 0.95 – 1.02. The θ-h relationships deviated from the 1:1 line for wet soil conditions. In absolute terms, the deviations were generally smaller than 0.05 $cm^3\ cm^{-3}$ for θ, except for part the top layers of the vertisol and mollisol where deviation up to 0.1 $cm^3\ cm^{-3}$ occurred under wet conditions. If compared at the same θ, the estimates of hydraulic conductivity (k) contained little error.

This test thus indicates that soil texture data from $P_{TF}RD_B$ and actual field measurement may give similar result for the θ-h-K relationships, but that uncertainty in the soil bulk density can interfere with the parameterization of the θ-h-K relationships.

The importance of these deviations will, of course, depend on the range of soil water contents involved, and on the types of effect that soil water content may have on further processes and output indicators. We tested this for a 10-year period of a simple agroforestry system, with the actual field measurements, as input for the Wösten PTF's, to predict θ for the same h at different soil types

4 IMPACTS ON WATER BALANCE PREDICTIONS OF WANULCAS

WaNuLCAS model version 2.1 (Van Noordwijk and Lusiana, 2000) was used to test the data from $P_{TF}RD_B$ and actual field measurement as input for Wösten PTF's to predict the water balance effects of this uncertainty in θ-h-K relationships. Site-specific files for Lampung were made for climate data and soil characteristics other than those derived from the PTF's, generally following Suprayogo (2000). A *Paraserianthes falcataria* + maize agroforestry system was simulated with a 10 year growing period and maize planted (twice a year) for the first 6 years.

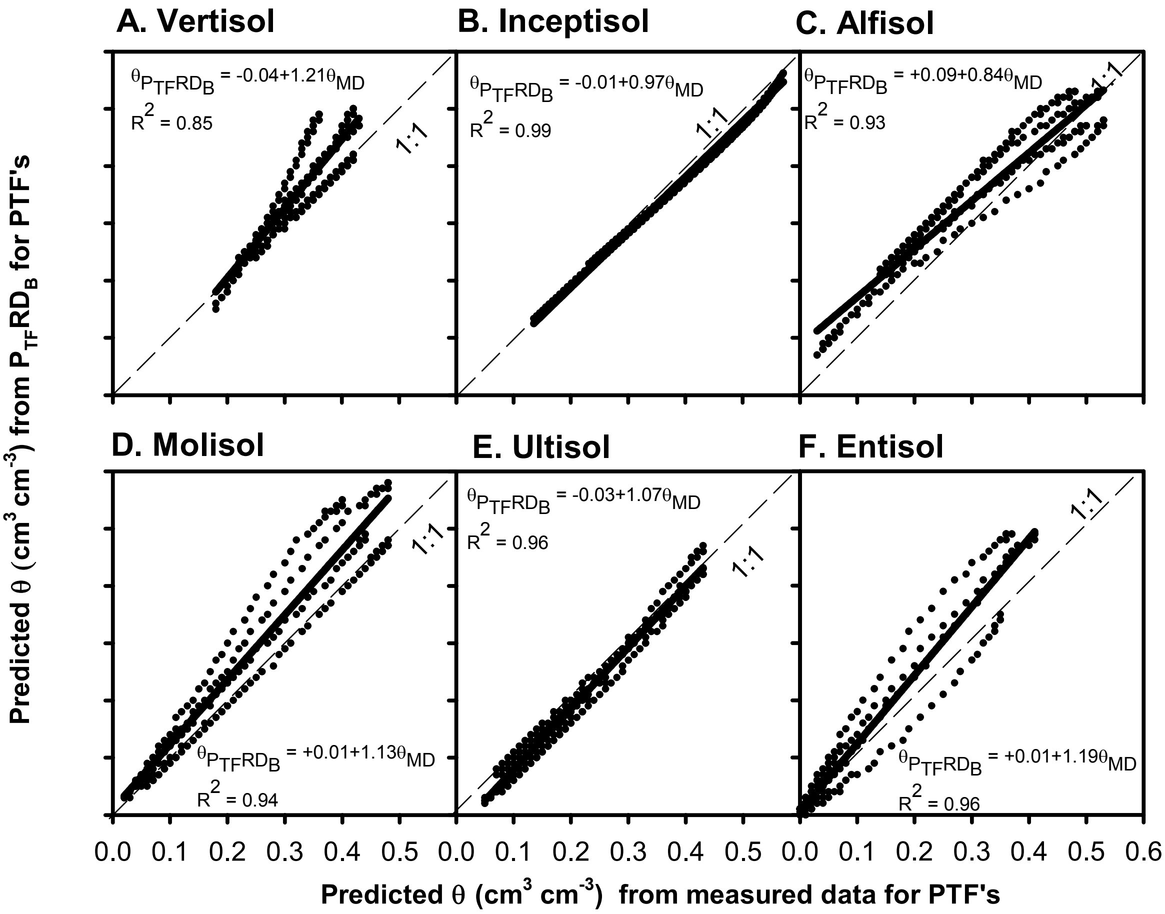

Figure 1. Comparison of the volumetric soil water contents (θ) estimates from $P_{TF}RD_B$ estimates and from actual field measurements, as input for the Wösten PTF's to predict θ for the same h at different soil types

In a 'simulation experiment', the six soil types of Table 4 were used for predicting the water balance of this agroforestry system, everything else being equal. The following outputs of the simulations were recorded:

1. Total amount of water in a 100 cm soil depth,
2. Cumulative water uptake by the 12 crops,
3. Cumulative tree water uptake over 10 years,
4. Total amount of water evaporated from the soil surface,
5. Canopy interception and direct evaporation from leaf surfaces,
6. Cumulative amount of runoff,
7. Total amount of vertical water draining out from 100 cm soil depth,
8. Total amount of lateral water outflow over the 100 cm soil depth (in excess of lateral inflow).

4.1 Comparisons on a daily basis

WaNuLCAS predictions for the total amount of water in the soil profile, generally agreed between runs that used data from $P_{TF}RD_B$ and those that used actual soil measurements as input for the Wösten PTF's.

Crop transpiration (on a daily basis) simulations agreed, except for those using vertisol data. Predictions of daily tree transpiration showed a considerable spread, with a 15% over estimate on the inceptisol and 15% underestimate on the entisol if the simulations with PTF's from measured soil data is taken as a point of reference. Similar deviations (with a 20% over- or underestimate) were obtained for soil evaporation, while there was no trend in the deviations for canopy interception. For runoff, and vertical water drainage deviations were largest on the vertisol, although values for higher flow rates agreed. For subsurface lateral flow the inceptisol showed the largest discrepancy.

4.2 Crop and tree production

While a number of the daily fluxes showed considerable divergence, predictions of maize yield and wood production were not sensitive to the way the soil physical input data were derived.

Table 3. Slope (a) and percentage of variation accounted for (R^2) of regression equation of **daily values** (Y_{PTF} = a Y_{PTFRDB}) for a 10 year WaNuLCAS simulation of a tree-maize system, based on actual field measurements for 6 soils or estimates derived from the $P_{TF}R_{DB}$ database; for maize yield the equation used was Y_{PTF} = a + b Y_{PTFRDB}. Slope parameters > 1.2 or < 0.8, and R^2 values < 0.8 are printed in bold.

	Vertisols		Inceptisols		Alfisols		Mollisols		Ultisols		Entisols	
	a	R^2	a	R^2	a	R^2	a	R^2	a	R^2	A	R^2
$\theta_{0\text{-}100}$	1.15	0.86	0.92	0.79	1.11	0.97	1.10	0.96	0.95	0.99	**1.22**	**0.49**
ET-maize	1.02	0.94	0.97	0.99	1.00	0.99	1.02	0.99	0.99	0.99	1.00	0.99
ET-tree	0.99	**0.66**	1.15	**0.61**	1.05	0.80	0.94	0.81	0.99	0.82	0.84	**0.53**
E-soil	1.01	**0.67**	0.81	**0.73**	0.89	0.86	1.07	0.81	0.98	0.88	**1.27**	0.97
E-interception	1.02	0.99	0.98	0.98	0.99	0.99	1.01	0.99	0.98	0.99	0.97	0.99
Runoff	0.76	0.90	0.92	0.96	1.04	0.99	1.00	0.99	0.97	0.99	0.95	0.99
Drainage	1.29	**0.71**	0.86	0.90	0.93	0.98	1.00	0.99	1.03	0.99	1.08	0.97
Lateral Flow	1.16	**0.58**	0.76	**0.72**	0.85	0.96	1.09	0.99	1.07	0.98	**1.22**	0.95
Maize yield a	0.68	.	0.45	.	0.55	.	0.08	.	0.01	.	0.77	.
b	0.92	0.89	0.88	0.98	1.12	0.94	1.01	0.98	0.98	0.98	0.72	0.96
Wood yield	1.15	0.96	0.92	**0.79**	1.11	0.97	1.10	0.96	0.95	0.99	**1.22**	0.99

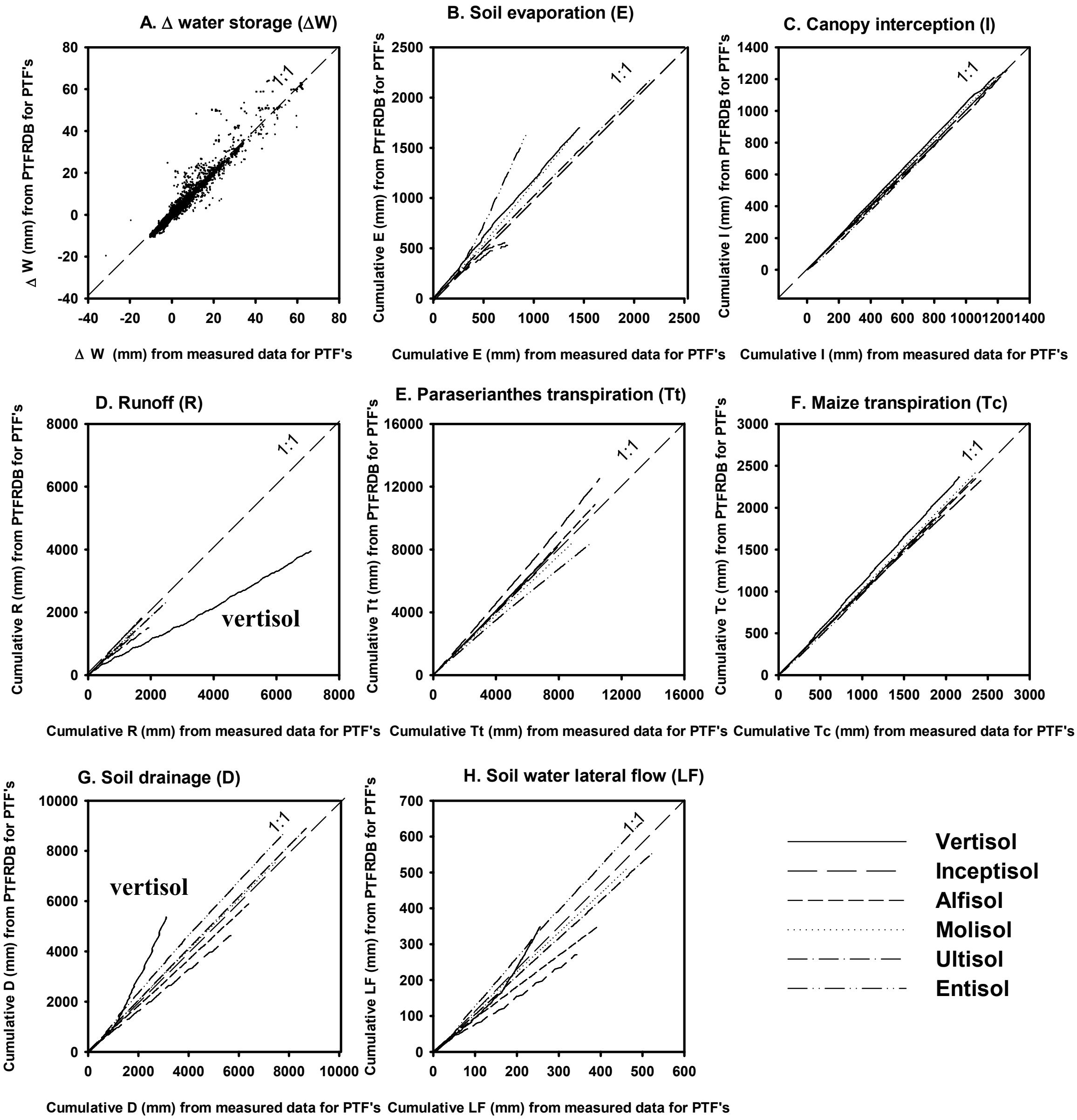

Figure 2. Cumulative effects on the terms of the plot-level water balance, for the simulations of Table 3 (N.b. the slope of the cumulative error can differ from that in 'daily error', due to 'compensation' effects)

4.3 Cumulative water balance effects

The consistency for the crop yield and tree production can be reconciled with the considerable divergences in part of the daily fluxes in the various simulations, by considering the cumulative evolution of the various terms of the water balance on the various soils (Fig. 2).

Overestimates on one day may be compensated by underestimates the next, leading to relatively small deviations from the 1:1 line. The main 'consistent' divergence was found in the form of an overestimate of vertical drainage and equivalent underestimate for surface runoff on the vertisol, when we take the PTF's with measured soil parameters as basis for the comparison. A consistent overestimate of soil evaporation on the entisol was apparently compensated by slight underestimates in tree transpiration and other terms.

5 CONCLUSIONS

Although simulations of the water balance of a simple agroforestry system with the WaNuLCAS model are sensitive to the parameterization of soil physical relationships, it appears to be acceptable to derive these from soil texture classes rather than from full measurements of soil texture. Uncertainties in estimates of soil organic matter content and/or soil bulk density, can lead to divergence of the simulations, with the largest effects on the partitioning between surface runoff and vertical drainage of the vertisol included in the comparison. Other effects stay within a 10% margin when considered at cumulative scales, although daily values of especially tree water use can vary considerably more. Given the uncertainty in other parameter domains, however, it may be sufficient to derive soil texture data by field estimates of texture classes. Real measurement of soil bulk density probably has highest priority in improving model accuracy.

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