Soil water dynamics and availability for citrus and peanut along a hillslope at the Sunjia Red Soil Critical Zone Observatory (CZO)

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Abstract

The hillslopes of red soils (Ultisols) in southern China are intensively cultivated for cash crops and fruit trees. During the rainy monsoon, soil erosion is prevalent, whereas a summer/autumn dry season induces drought stress. Crops respond differently to these stresses, and have different effects on soil water regime. This study used a combination of combination of field observation and HYDRUS-2D modeling to assess the soil water dynamics and plant available water for peanut (*Arachis hypogaea*) and citrus (*Citrus sinensis*) at Sunjia Red Soil Critical Zone Observatory (CZO). Between April 1, 2012 and March 31, 2014, surface runoff and moisture content at 5, 20, 40, and 80 cm depths of both land uses were monitored at up, middle and foot slope positions along a hillslope. Results indicate that the citrus plot had higher soil water content at 5 cm depth during the dry season, while lower at 20, 40 and 80 cm depths throughout the year, compared to the peanut plot. As expected, the soil water content was higher at foot slope, compared to up slope, and in deeper depths than near surface. We observed limited soil water availability to peanut during mid-July to August, and to citrus from mid-July to mid-November. Compared to the peanut plot, the citrus plot generally showed 12-28% greater evapotranspiration, 3-4 times less runoff, and 2-57% greater deep drainage. These differences were greater at the up slope position. Our data and HYDRUS-2D simulation suggest that the deep-rooted citrus reduced runoff during the rainy season by improving macropore flow and canopy intercept, and minimized the soil water stress during the dry season by utilizing water from deeper soil. Thus, we recommend trench planting of citrus along with peanut intercropping on hilly red soils as sustainable agricultural practices.

Keywords: Critical Zone Observatory; HYDRUS-2D; Soil moisture; Soil structure; Sustainable agriculture;

1. Introduction

Water shortage and soil erosion are the two main threats to sustainable agriculture in hilly red soil region with a monsoon climate in southern China. Heavy monsoonal rain with peaks occurring between April and June causes serious soil erosion. The red soil region becomes the second largest area of soil erosion just after the Loess Plateau in China (Zhao, 2002). On the other hand, the limited rainfall during late summer/autumn leads to an intensive drought stress to crop in the clayey red soils (D'Angelo et al., 2014; Zepp et al., 2005). The challenge, therefore, is to find ways of utilizing the red soil for sustainable agriculture. Knowledge of soil moisture and soil water fluxes under varying soil hydraulic properties as a consequence of different types of land use can help us improve the soil-plant system to resist these two stresses.

Land use type plays an important role in adjusting soil moisture and hydraulic properties through changing soil physical and biological properties (Fu et al., 2003; Hu et al., 2009). Different land uses transform the soil physical properties such as soil structure, bulk density, and pore size distribution (Yu et al., 2008), and biological properties such as root distribution, residue return and organisms activities, and soil organic carbon contents (Pulleman et al., 2000). The changes in soil properties, in turn, influence the storage and redistribution of soil water (Dörner et al., 2010; Rasse et al., 2000) and soil hydraulic conductivity functions (Zhou et al., 2008; Zhang et al., 2016). The land slope further affects the redistribution of soil moisture and water flow through surface runoff and subsurface lateral flow along the slope (Robinson et al., 2008; Wang et al., 2011). Nevertheless, due to the heterogeneity of soil properties and landscape, the spatio-temporal variation of soil moisture remains a challenge in the hydrological and soil sciences (Vereecken et al., 2007).

Soil hydraulic properties, particularly plant available water within the effective root zone, are essential data for determining soil water stress and water fluxes. Red soils are found to be highly sensitive to drought, which limits the exploitation of clayey red soils for agriculture. This high sensitivity to drought might be related to the low proportion of plant available water and the poor water holding capacity (De Silva et al., 2008). Lower water holding capacity of soil further affects resilience and stability of production systems in the face of an increased frequency of extreme runoff events during the rainy monsoon. In the red soil of southern China, seasonal arable crops (e.g., peanut, watermelon) are cultivated only during April to August (He et al., 2001). Under such circumstances, citrus trees with deep root system (≈100 cm) (Zhou et al., 2009) may have an advantage to being established on hillslope by mitigating the effect of both drought and runoff losses. However, a comprehensive knowledge about the soil water availability during the different seasons of a year, especially during the dry season, is lacking.

To find out best use of soil moisture under natural conditions and to make future predictions about the hydrological processes, agro-hydrological simulation models are commonly used to provide precise and detailed knowledge of the soil water dynamics and crop water use (Kikuchi et al., 2015). The HYDRUS-2D model has been used world-wide to simulate soil water dynamics and water fluxes under different types of land use (Šimůnek et al., 2011). This model allows for the specification of root water uptake and adjustment of soil hydraulic properties for different scenarios. Here, we provided a site specific validation of HYDRUS-2D under different land uses for a red soil hillslope. A detailed soil monitoring network exists at the Sunjia Red Soil Critical Zone Observatory (CZO), with multiple years of soil water content, surface runoff, and metrological data. The objective of the present study was to assess the soil water content and the associated soil water stress, surface runoff and deep drainage for peanut monoculture and citrus on hilly red soil, using a combination of field observation and HYDRUS-2D simulation approach.

2. Materials and methods

2.1. *The study site*

This study was carried out on the erosion plot experiment (Fig. 1) at the Sunjia watershed, belonging to the subtropical monsoon climate region. The watershed is situated 4 km from the Ecological Experimental Station of Red Soil, Chinese Academy of Sciences (28^{0}130′N and 116^{0}550′E, altitude 50 m), Jiangxi province, China. Sunjia is the Red Soil Critical Zone Observatory (CZO) established in China. Citrus orchard and peanut crop are typical land uses in the red soil region, accounting for 20% and 48% of land in the watershed, respectively. The red soil is classified as Ultisol in the USDA taxonomy (Soil Survey Staff, 2010), and has a clay loam to clay texture at the watershed (Table 1). Monitoring was conducted for two land uses: a) peanut, planted continuously for 20 years from April to August after following a long fallow period, and b) citrus orchard, established 20 years ago with a plant density of 5 × 5 m.

2.2. Soil analysis

Disturbed soil and undisturbed 100 cm^3 cores were collected in Oct. 2011 from the citrus and peanut-fallow land uses with four repeats at 0-10 cm, 10-30 cm, 30-50 cm, and 50-100 cm depths at up, middle, and foot slope positions to determine the soil properties. Disturbed soils were air-dried, ground, and passed through a 2 mm sieve to determine some basic soil properties after following routine methods (Klute, 1986; Lu, 2000). The soil organic carbon (SOC) was determined by oxidation with potassium dichromate. Particle size distribution (sand, >50 μm; silt, 2-50 μm; and clay, <2 μm) was determined by the pipette method. Undisturbed soil cores were used to determine the soil bulk density, water retention curve from 0, -30, to -60 cm water potential was determined by sand box method and from -100, 330, -1000, -3000, to -15000 cm water potential were determined by a pressure chamber, and saturated hydraulic conductivity (K_s) was determined by the falling head method.

2.3. Rainfall, soil water, and runoff monitoring

From the peanut-fallow and citrus plots, the soil moisture and matric potential were monitored at 5, 20, 40 and 80 cm soil depth using FDR (Delta-T Devices Ltd, Model: ML2x Theta Probe, Cambridge, UK) and tensiometer (Irrometer, Co. Model: Watermark granular matrix, Riverside California, USA) probes, respectively. These were connected to a data logger (Delta-T Devices Ltd, Model: DL2e, Cambridge, UK). The monitored data at depths of 5, 20, 40 and 80 cm were representative of 0-10, 10-30, 30-50, and 50-100 cm soil layers. Along the slope, they were monitored at the up, middle and foot slope positions of the citrus plots (CU, CM, CF) and peanut plots (PU, PM, PF), located at approximately 30, 70 and 110 m distance from the top of the hill (Fig. 1). The soil water content and matric potential were recorded at every 6 hours and averaged to daily values. Each slope position had two replicates, but no significant difference was found, they were averaged to a single value. Along the slope, four erosion plots with a size of 6.0 m × 20.0 m were constructed at the up and foot slope positions of citrus and peanut fields for monitoring runoff and soil erosion (Fig. 1). The runoff at the lower end of plot was monitored by a tipping bucket system (Khan and Ong, 1997). The missing runoff at the middle slope was averaged the runoff observed at the up and foot slope positions. Meteorological data were collected from the Red Soil Station. The study period spanned two years from April 1, 2012 to March 31, 2014.

2.4. Numerical modeling of soil water balance

HYDRUS-2D (Šimůnek et al., 2011) was used to simulate the soil moisture dynamic, evapotranspiration and deep drainage. The water flow in the Richards equation incorporates a sink term to account for water uptake by plant roots as follows:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial h}{\partial z}-K(\theta)\right]-S(z,t) \quad (1)$$

where θ is the volumetric soil water content (cm^3 cm^{-3}), $K(\theta)$ is the unsaturated hydraulic conductivity (cm^3 day^{-1}), h is the water potential (cm), S(z, t) is the root water uptake (cm^3 cm^{-3} day^{-1}), t is time (day), z is the soil depth (cm). The root water uptake was simulated according to the Feddes model (Feddes et al., 1978). The soil hydraulic properties were expressed by van Genuchten-Mualem parameters (van Genuchten, 1980):

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{[1+|\alpha h|^n]^m} \quad (2)$$

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left(\frac{1}{1+(\alpha|h|)^n}\right)^m \quad (3)$$

$$K(h)=K_s S_e^{\tau}[1-(1-S_e{}^{1/m})^m]^2 \quad (4)$$

where S_e is the effective saturation, and θ_s and θ_r are the saturated and residual water content (cm^3 cm^{-3}), respectively; α, n, and m are the fitting parameters (dimensionless), and m is assumed to be 1-1/n. K_s is the saturated hydraulic conductivity (cm day^{-1}), and τ is a pore connectivity parameter, which is set to a default value of 0.5. In this study, in situ simultaneously monitored soil matric potential and water content datasets were used to obtain θ_s, θ_r, α, n and m

(m=1-1/n) parameters. During the soil drying period, more than 50 paired data of soil water content and matric potential (h= -2000 cm) were selected for determining the parameters of soil water retention curve. These fitted parameters (Table 2) were used as initial values for calibration process.

HYDRUS-2D was used to calibrate the dynamics of soil water with the parameters θ_s, θ_r, α, n, m, and K_s. The parameters of K_s, α, n and m (m=1-1/n) were optimized to yield a close match between the observed and simulated moisture contents from April 1, 2012 to March 31, 2013. Then, the model with calibrated parameters was validated on the entire year 2013-14 (April 1, 2013 to March 31, 2014). The model efficiency in calibration and validation years was evaluated by using root mean square errors (RMSE):

$$RSME = \left(\frac{1}{N}\sum(P-O)^2\right)^{1/2} \quad (5)$$

where N is the number of observations, and P and O are the modeled and observed values of soil water content, respectively.

2.5. Simulation domain and boundary conditions

The simulation domain was selected as one dimension (z= 100 cm) with four mesh lines at depths of 5, 20, 40 and 80 cm. The surface boundary condition consisted of atmospheric condition, while the bottom boundary at 100 cm soil depth was defined as free drainage. The actual evapotranspiration (ET_c) and deep drainage flux were predicted by HYDRUS-2D at up, middle and foot slope position, separately. ET_c was predicted when considering soil water content, crop type for citrus and peanut, and potential evapotranspiration (ET_p). The ET_p was obtained by multiplying the reference crop evapotranspiration (ET_0) by the crop age coefficient (K_c) (Allen et al., 1998):

$$ET_p = K_c\, ET_0 \quad (6)$$

The crop age coefficients of citrus and peanut crops were adjusted for the local climate according to FAO-56 guidelines for computing crop water requirements (Allen et al., 1998). ET_0 was calculated by the Penman–Monteith equation using the meteorological data from the Red Soil Station.

2.6. Assessment of plant available water and soil water stress

Plant available water during different seasons of the two years was assessed on the basis of the soil water content. From the soil water retention curve and the simulated field moisture data, the plant available water (PAW, mm) in a certain soil layer was calculated as follows:

$$PAW = (\theta_{\leq FC} - \theta_{PWP}) \times Z_j \times 10 \quad (7)$$

with $\theta_{\leq FC}$ is the soil water content when the water potential was less than or equal to the field capacity (h≤-330 cm) ($cm^3\ cm^{-3}$), and θ_{PWP} is the soil water content at permanent wilting point (PWP) of h=-15 000 cm ($cm^3\ cm^{-3}$). z_j is the investigated soil depth (cm) at *j* horizon, where *j* indicates the four investigated soil horizons: 0-10, 10-30, 30-50, and 50-100 cm.

The soil water stress in the peanut-fallow and citrus land uses at different land slope positions was calculated by the ratio of ET_c and ET_p rate (Kozak et al., 2006):

$$Soil\ water\ stress = \frac{ET_c}{ET_p} \quad (8)$$

3. Results

3.1. Climate and basic soil properties of the experimental site

The monthly average rainfall, air temperature, and ET_0 are presented in Fig. 2. The experimental area receives plenty of rainfall, which is unevenly distributed among different seasons. In 2012-13 (Apr. 2012-Mar. 2013), it received 2527 mm rainfall which was distinctly higher than the rainfall of 1622 mm in 2013-14 (Apr. 2013-Mar. 2014) and the 50-year average (1795 mm). In 2013-14, the rainfall exceeded 250 mm per month during monsoon wet season (Mar.- Jun.), while it was less than 50 mm per month during the dry season (Jul.-Oct.), which is typical for this area. Four months of the monsoon wet season received 54.1% and 70.1% of total rainfall during 2012-13 and 2013-14, respectively, while the corresponding values for the four months of the dry season were 22.8% and 6.7%. ET_0 exceeded the rainfall from July to October in 2013-14, causing a seasonal drought. However, in 2012-13, this was only a feature in July and October. Thus, the climatic data in the year 2013-14 were typical for this area.

The basic soil properties were land use dependent (Table 1). The soil texture was clay loam for peanut and citrus plots up to 50 cm depth, while 50-100 cm soil of both the field was clayey in nature. The clay content generally presented a slight increase from up slope to foot slope at the same depth. The bulk density increased but the soil organic C decreased with increasing soil depth at all sites. At 0-10 cm soil depth, comparatively higher bulk density and soil organic C was observed in the citrus orchard compared to the peanut field. At a given soil depth, the citrus orchard showed generally 2 times higher K_s than the peanut field.

3.2. Effects of land use and slope position on soil water

The soil water content dynamic was dependent on land use, slope position and soil depth (Fig. 3 and 4). The deeper soil depths showed generally higher water content with steady temporal variation, compared to the upper soil layers. At 5 cm depth, the soil water content was generally similar between the two land uses during the wet season and winter season. In the dry season, however, citrus plots showed higher water content than the peanut-fallow plots. In contrast, in the deeper soil depths, water content of citrus plots was lower than the peanut-fallow plots throughout the year. The slope position effect indicates that the soil water content increased from the up slope to the foot slope in both land uses. As an average of two years, the soil water contents at the middle and foot slope positions were higher by 5.0% and 6.5% in citrus, and by 7.9% and 10.3% in the peanut field, respectively, compared to those at the up slope position.

The fitted van Genuchten parameters θ_s and θ_r were nearly the same for the two land uses, but α was greater in the citrus plot than in the peanut-fallow plot (Table 2). The optimized K_s ranged from 3.5 to 9.80 and from 6.1 to 15.0 cm day^{-1} for the peanut-fallow and citrus plots, respectively, where the highest values were observed for the surface soil layer (Table 2). The optimized K_s values were slightly lower than the measured ones, as shown in Table 1. The data pairs of observed and predicted water content from the peanut and citrus plots during the calibration (Fig. 3) and validation years (Fig. 4) showed good performance for HYDRUS-2D for each land slope position and for each soil depth, as indicated by the RMSE (Table 3). The decreased RMSE values with increasing depth indicate a better fit of the model for the deeper depths, where the soil water content was steady. In general, model efficiency was better for predicting the soil water at the peanut-fallow plot than at the citrus plot, as indicated by the smaller RMSE values.

3.3. Effects of land use and slope position on plant available water (PAW) and soil water stress

Land use had a significant effect on PAW (Fig. 5) and soil water stress (Fig. 6) at different soil depths and slope positions. In the wet season, the PAW usually touched its maximum capacity in all soil depths for both land uses. Hence, only minimal soil water stress was observed on a few occasions during the wet season. Soil water stress to peanut and citrus was observed due to depletion of PAW below its maximum capacity in Jul-Oct of the dry season, particularly in 2013. Thus, peanut was suffered the drought stress at its late stage (Fig. 6). During later stages of the dry period, all of PAW in the soil surface was not only depleted, but the soil water content was well below the permanent wilting point, as indicated by the negative values of PAW. Nevertheless, deeper soil depths during the dry period had some quantity of PAW. A slight soil water stress to citrus was also observed during the winter season (Fig. 6). In different soil layers of the citrus plot, the PAW was generally lower than that of the peanut-fallow plot. Higher PAW and lower soil water stress was observed at the foot slope position compared to the middle and up slopes, especially in the peanut-fallow plot.

3.4. Water fluxes in hilly red soil under peanut-fallow and citrus land uses

The water balance components were dependent more on the land use than on slope position (Table 4). For the two year data, on average, the peanut-fallow land use at different slope positions showed 3.0-4.3 times higher runoff than the citrus orchard. Runoff occupied 13-22% of rainfall in the peanut-fallow plots but only 4-6% in the citrus plots due to canopy intercept. Runoff, which was monitored at the erosion plot, was not highly dependent on the slope position. The HYDRUS-2D simulated ET_c was 25-28% and 12-19% higher at the citrus plot compared to the peanut-fallow plot in 2012-13 and 2013-14, respectively. The ET_c at the foot slope was 4-6%

and 7-12% greater than at the up slope of the peanut and citrus plots, respectively. The deep drainage estimated by HYDRUS-2D was 30-34% and 9-14% of rainfall in 2012-13 and 2013-14, respectively. It was 2-18% and 4-57% greater at the citrus plot than at the peanut-fallow plot in 2012-13 and 2013-14, respectively. There was a greater deep drainage at the up slope than at the foot slope in the citrus plot, whereas the slope dependence was not observed for the peanut-fallow land use. The change in soil water storage during a one year was minor.

4. Discussion

4.1. No tillage in the citrus plot improved hydraulic properties

The higher bulk density of the surface layer in the citrus plot relates to the reduced tillage intensity (Liu et al., 2013), compared to the peanut-fallow plot. Frequent tillage causes the breakdown of soil structure, thereby producing loose soil with lower bulk density in the peanut plot (Zhang et al., 2016). However, a greater K_s was observed in the citrus plot, compared to peanut-fallow plots (Table 1). Higher K_s may originate from the improved soil structure due to reduced tillage intensity and the extensive root network of the citrus trees, thereby ensuring higher effective macro-porosity (Zhang et al., 2016). On the other hand, frequent tillage compacted subsoil layer and broke down the continuity of pores in the peanut plot, which generally formed a poor permeable horizon. We observed low clay content in the surface layers at the upslope position that might be due to the transport of clay fractions with surface runoff along the slope.

4.2. Seasonal dynamics of soil water and water fluxes under peanut and citrus land uses

A similar water content in the soil surface layer between the two land uses during wet season and winter season was ascribed to a greater rainfall than the ET_c (Table 4). During the dry season, however, higher water content in the surface layer in the citrus field than in the peanut-fallow might result from the lower soil evaporation by citrus tree coverage. Interestingly, compared to peanut, the lower water content in the deeper soil layers of the citrus field was related to more root water uptake from deeper soil (Wang et al., 2011). This can be explained by the fact that citrus tree active rooting zone is usually 100 cm but it is 50 cm for peanut crop (Allen et al., 1998). Our results are consistent with by the findings of Zhou et al. (2009) that a significant amount of root water uptake by citrus trees was from deeper soil. Greater water content in deeper soil layers at the foot slope than at the up slope, especially in case of the peanut-fallow plot, was a result of the surface runoff and subsurface lateral flow. Wang et al. (2011) reported that the subsurface lateral flow was reduced by 9.2% of annual rainfall in the agroforestry than in the mono crop system in a year. This can be further explained by the fact that the low permeable subsurface layer, which was compacted by tillage in the peanut plot, improved lateral water flux along slope.

The reduced surface runoff in the citrus plot resulted from the interception of rainfall by citrus trees and the increased macropore flow (Table 4). Additionally, tree canopy decreases the rainfall intensity, ultimately leading to lower runoff and erosion (Lv et al., 2014). Higher deep drainage flux, predicted by HYDRUS-2D, in the citrus plot, was a result of higher K_s value (Tables 1 and 2) and an increased macroporosity due to the biological activities and reduced tillage. At the same experimental site, Zhang et al. (2016) found that macroporosity was more stable and higher in the citrus field (2.43 $cm^3\ m^{-3}$, coefficient of variance (CV) =75 %) than in the peanut field (1.72 $cm^3\ m^{-3}$, CV=117 %) and contributed more to infiltration in the citrus than in the peanut/watermelon field. Thus, citrus on hilly clayey soils can gain an advantage from the high water permeability, which not only reduces the surface runoff during heavy rainfall events but also increases the deep drainage.

4.3. Soil water stress alleviated in the citrus plot

A less soil water stress in the citrus plot than in the peanut plot during the late stage of the peanut season (Jul-Aug) clearly indicates the ability of citrus roots to take up water from deeper soil depth, which had more quantity of PAW (Figs 5 and 6). During the dry season of 2013-14, soil water stress values in the citrus plot reached to a minimum level of 0.2, conforming the drought like conditions of the red soil (Tang et al., 2008; Zepp et al., 2005). However, almost all of the PAW was depleted from the 0-10 and 10-30 cm layers during this period, limiting water availability to peanut while citrus trees utilized soil water from deeper layers. The higher PAW at the foot slope position was more a function of water inflow from the upslope in the form of surface runoff or subsurface lateral flow from the upwards slope (Wang et al., 2011).

4.4. HYDRUS-2D parameterization and model application

The measured data produced higher values of K_s than did the optimized values, which might be a result of the disturbance and cut-through of dead end pores during sampling soil cores (Stolte et al., 2003). On the other hand, if the use of neural network analysis, which is based on the soil texture, soil bulk density and water retention at the two water potentials, i.e. -330 and -15000 cm (Schaap et al., 2001), may cause misleading results due to soil structural changes. In addition, van Genuchten parameters n and α were optimized due to the soil structure heterogeneity in the presence of biological channels and macropores. Similar to many other studies (Fan et al., 2015; Whitaker et al., 2003), parameter optimization was done on a trial and error basis to obtain a close match between measured and predicted moisture contents. We observed reasonably good correlation between the measured and simulated soil water content, with a better fit of model to deeper soil depths (Table 3). Moreover, the HYDRUS-2D simulation results with close resemblance were the best alternative for the missing data, e.g., when the data logger was not working (Figs 3 and 4). Furthermore, deeper drainage and ETc, which are difficult to monitor or measure *in situ*, could be predicted by HYDRUS-2D model. The deep drainage with accounting for 9-34% of the rainfall was consistent with Wang et al. (2011) who reported 14.3-41.6% of annual rainfall in the hilly red soil. Thus, modeling together with accurate monitoring can provide an integrated approach for assessing field scale soil water dynamics and water flux through the critical zone interface.

5. Conclusions

We evaluated the soil water dynamics and water flux as affected by land uses, i.e., monoculture peanut and citrus, and slope positions at Sunjia Red Soil CZO by integrating monitoring and simulated 2-year data. Our conclusions are summarized as follows:

a) The citrus plot showed a greater soil water content at the surface layer during the dry season, and a less soil water content at deeper soil layers throughout the year than the peanut plot. The citrus plots generated greater ET_c, less runoff, greater deep drainage than the peanut plot.

b) Monitoring and HYDRUS-2D simulation results concluded that citrus is a better choice than the monoculture peanut on hilly clayey red soils because a) during the monsoon rainy season, citrus reduced surface runoff with enhanced hydraulic properties, and b) during the dry season, the deep-rooted citrus could extract water from the deeper soil.

c) Based on the findings of the moisture content and water flux from the peanut and citrus fields, we suggest the contour planting of citrus together with peanut intercropping should reduce soil erosion during the rainy season, while the trenches can store more moisture for citrus at the onset of drought conditions.

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Table
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Table1 Soil basic and hydraulic properties of four soil layers at different slope positions under citrus and peanut-fallow land uses.

Land use	Depth	SOC[§]	Bulk density	Sand	Silt	Clay	K_s
	cm	$g\ kg^{-1}$	$Mg\ m^{-3}$	------------%------------			$cm\ day^{-1}$
PU[¶]	0-10	11.3	1.36	39.0	28.1	32.9	10.2
	10-30	7.4	1.41	38.5	27.8	33.7	8.5
	30-50	4.3	1.45	29.3	34.0	36.7	8.4
	50-100	4.3	1.46	29.5	31.5	40.0	7.4
PM	0-10	11.5	1.35	38.5	25.0	36.5	12.2
	10-30	4.7	1.40	37.4	24.8	37.8	9.1
	30-50	3.6	1.44	36.8	24.8	38.4	8.9
	50-100	3.0	1.47	34.4	24.7	40.9	8.1
PF	0-10	11.6	1.34	38.5	24.5	37.0	14.3
	10-30	4.6	1.41	39.3	23.6	37.1	9.1
	30-50	4.0	1.46	35.5	25.2	39.3	8.8
	50-100	3.6	1.48	34.8	23.6	41.6	7.9
CU	0-10	16.6	1.39	40.2	25.0	34.8	25.2
	10-30	5.1	1.42	43.2	25.0	35.8	23.1
	30-50	3.6	1.44	31.9	29.5	38.6	17.0
	50-100	3.6	1.45	29.9	29.5	40.6	16.2
CM	0-10	16.0	1.41	35.0	28.5	36.5	23.1
	10-30	5.5	1.41	35.9	24.8	39.3	19.2
	30-50	4.4	1.43	35.7	24.8	39.5	18.2
	50-100	4.1	1.47	33.0	24.9	42.1	15.9
CF	0-10	13.6	1.41	37.4	26.5	36.1	24.3
	10-30	5.4	1.42	36.3	26.3	37.4	20.5
	30-50	4.2	1.44	33.1	27.5	39.4	17.3
	50-100	3.5	1.46	30.3	28.0	41.7	14.2

[§]SOC, soil organic carbon; K_s, saturated hydraulic conductivity

[¶]PU, PM, PF, CU, CM and CF are peanut-fallow and citrus land use at up, middle and foot slope positions, respectively. The same descriptions are in below Tables.

Table 2 Fitted parameters of van Genuchten-Mualem soil hydraulic functions for four soil layers under citrus and peanut-fallow land uses.

Land use	Depth cm	θ_r[§]	θ_s	α	n	r^2	K_s cm day^{-1}
		---$cm^3 cm^{-3}$----					
PU	0-10	0.065	0.41	0.027 (0.020[†])	1.34 (1.29)	0.94	(9.8)
	10-30	0.062	0.41	0.023 (0.015)	1.36 (1.33)	0.89	(8.2)
	30-50	0.059	0.40	0.022 (0.015)	1.38 (1.36)	0.96	(7.1)
	50-100	0.057	0.39	0.020 (0.013)	1.43 (1.41)	0.97	(4.7)
PM	0-10	0.066	0.41	0.026 (0.025)	1.25 (1.32)	0.92	(9.1)
	10-30	0.064	0.41	0.025 (0.023)	1.35 (1.34)	0.84	(7.0)
	30-50	0.061	0.40	0.023 (0.020)	1.40 (1.36)	0.96	(6.5)
	50-100	0.057	0.39	0.019 (0.018)	1.45 (1.40)	0.97	(4.6)
PF	0-10	0.065	0.41	0.025 (0.022)	1.30 (1.22)	0.92	(8.5)
	10-30	0.062	0.40	0.023 (0.021)	1.32 (1.29)	0.89	(6.3)
	30-50	0.059	0.40	0.022 (0.019)	1.39 (1.33)	0.94	(5.0)
	50-100	0.055	0.39	0.017 (0.018)	1.45 (1.39)	0.98	(3.5)
CU	0-10	0.059	0.42	0.035 (0.040)	1.37 (1.32)	0.90	(15.0)
	10-30	0.057	0.41	0.032 (0.034)	1.39 (1.38)	0.94	(10.0)
	30-50	0.056	0.40	0.029 (0.032)	1.44 (1.42)	0.89	(8.7)
	50-100	0.055	0.39	0.027 (0.030)	1.48 (1.47)	0.85	(6.1)
CM	0-10	0.062	0.42	0.031 (0.036)	1.45 (1.37)	0.83	(15.0)
	10-30	0.061	0.41	0.030 (0.031)	1.49 (1.40)	0.94	(10.5)
	30-50	0.060	0.41	0.026 (0.030)	1.55 (1.42)	0.85	(8.8)
	50-100	0.055	0.30	0.024 (0.028)	1.57 (1.48)	0.85	(6.2)
CF	0-10	0.059	0.42	0.032 (0.034)	1.41 (1.29)	0.90	(14.5)
	10-30	0.056	0.41	0.028 (0.029)	1.45 (1.35)	0.89	(10.6)
	30-50	0.057	0.41	0.026 (0.028)	1.48 (1.40)	0.88	(9.8)
	50-100	0.055	0.40	0.022 (0.025)	1.55 (1.44)	0.84	(7.1)

[§]θ_r and θ_s, residual and saturated volumetric water content, respectively; α, reciprocal value of air entry pressure; *n*, shape parameter; r^2, coefficient of determination; K_s, saturated hydraulic conductivity; [†] values in parentheses optimized during calibration

Table 3: Root mean square errors (RMSE) between observed and modeled soil water content at different slope positions under peanut-fallow and citrus land uses

Land use	Calibration (Apr. 2012-Mar. 2013)				Validation (Apr. 2013-Mar. 2014)			
	5 cm	20 cm	40 cm	80 cm	5 cm	20 cm	40 cm	80 cm
PU	0.024	0.013	0.012	0.008	0.034	0.015	0.012	0.011
PM	0.020	0.018	0.012	0.011	0.025	0.018	0.017	0.015
PD	0.020	0.015	0.011	0.011	0.022	0.016	0.015	0.013
CU	0.033	0.017	0.017	0.014	0.036	0.019	0.019	0.018
CM	0.021	0.019	0.015	0.010	0.025	0.022	0.022	0.019
CD	0.027	0.019	0.014	0.013	0.032	0.021	0.015	0.017

Table 4: Water balance components (mm) at three slope positions in 0-100 cm depth of peanut-fallow and citrus land uses during Apr. 2012-Mar. 2013 (calibration period) and Apr. 2013-Mar. 2014 (validation period).

Land use	Rainfall	ET_0[§]	ET_c	Runoff	Deep drainage	ΔS
			Year Apr. 2012-Mar. 2013 (Calibration period)			
PU	2527(1470[†])	1267 (666)	1195 (553)	584 (448)	736 (475)	12 (-6)
PM	-	-	1238 (574)	542 (424)	741 (480)	6 (-8)
PF	-	-	1247 (590)	520 (399)	743 (490)	17 (-9)
CU	-	-	1496 (748)	136 (116)	869 (610)	26 (-4)
CM	-	-	1568 (786)	148(128)	800 (565)	11 (-8)
CF	-	-	1599 (798)	150 (139)	761 (535)	17 (-2)
			Year Apr. 2013-Mar. 2014 (Validation period)			
PU	1622 (895)	1285 (664)	998 (513)	355 (261)	247 (142)	22 (-21)
PM	-	-	1021 (525)	338 (247)	242 (146)	21 (-23)
PF	-	-	1054 (532)	320 (233)	241 (152)	07 (-22)
CU	-	-	1120 (613)	99 (75)	387 (232)	16 (-29)
CM	-	-	1233 (687)	105 (78)	271 (159)	13 (-29)
CF	-	-	1250 (692)	107 (82)	250 (153)	15 (-32)

[§]ET_0, reference evapotranspiration; ET_c, actual evapotranspiration simulated by HYDRUS-2D; ΔS, change in soil water storage; [†] values in parentheses reflect the water flux the peanut season.

FIGURE CAPTIONS

Fig. 1. Schematic view of the experimental site. PU, PM, PF, CU, CM and CF are peanut-fallow and citrus land uses at up, middle and foot slope positions, respectively.

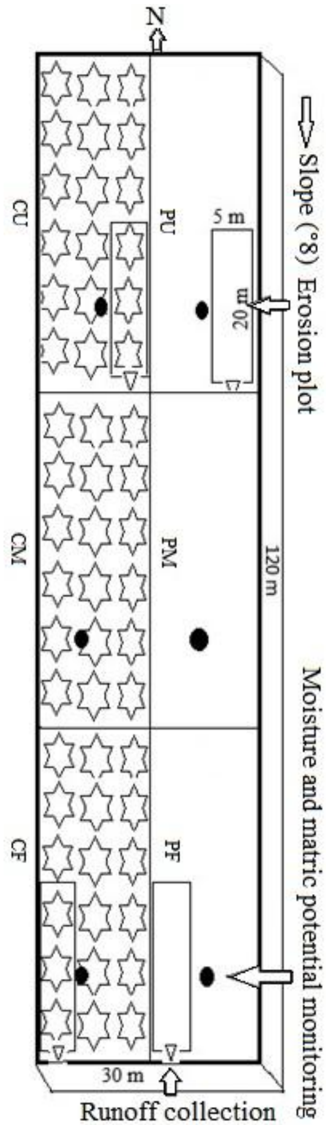
Fig. 2. Monthly average rainfall, reference crop evapotranspiration (ET_0) and air temperate during the study period from Apr. 2012 to Mar. 2014.

Fig. 3. Daily monitored (M) and HYDRUS-2D simulated (S) soil water content at different depths and slope positions of peanut-fallow and citrus land uses during calibration year from Apr. 2012 to Mar. 2013. Up, Mid, and Foot indicate the slope positions.

Fig. 4. Daily monitored (M) and HYDRUS-2D simulated (S) soil water content at different depths and slope positions of peanut-fallow and citrus plots during validation year from Apr. 2013 to Mar. 2014. Up, Mid, and Foot indicate the slope positions.

Fig. 5. Dynamics of plant available water (PAW) at different depths of the peanut-fallow and citrus plots. Up, Mid, and Foot indicate the slope positions. Note: Negative values on Y axis indicate the water content below permanent wilting point.

Fig. 6. Changes in soil water stress in the peanut season and citrus plots. The value of stress factor 1 indicates no water stress.



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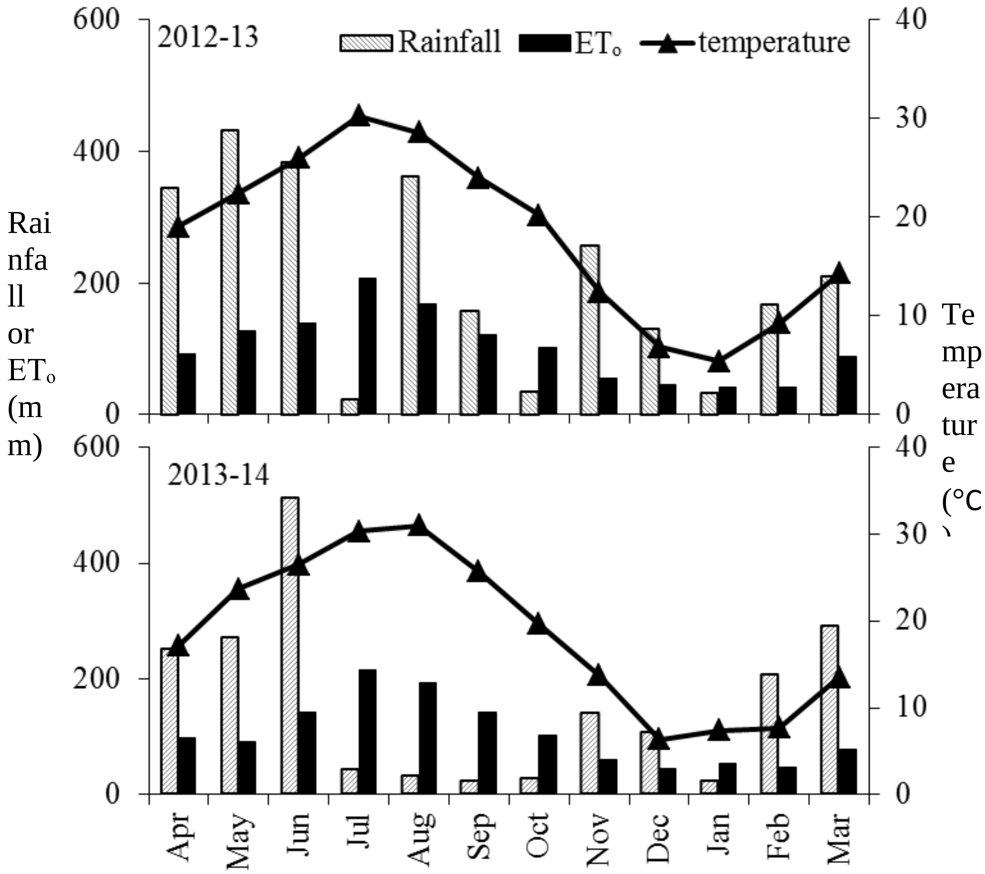

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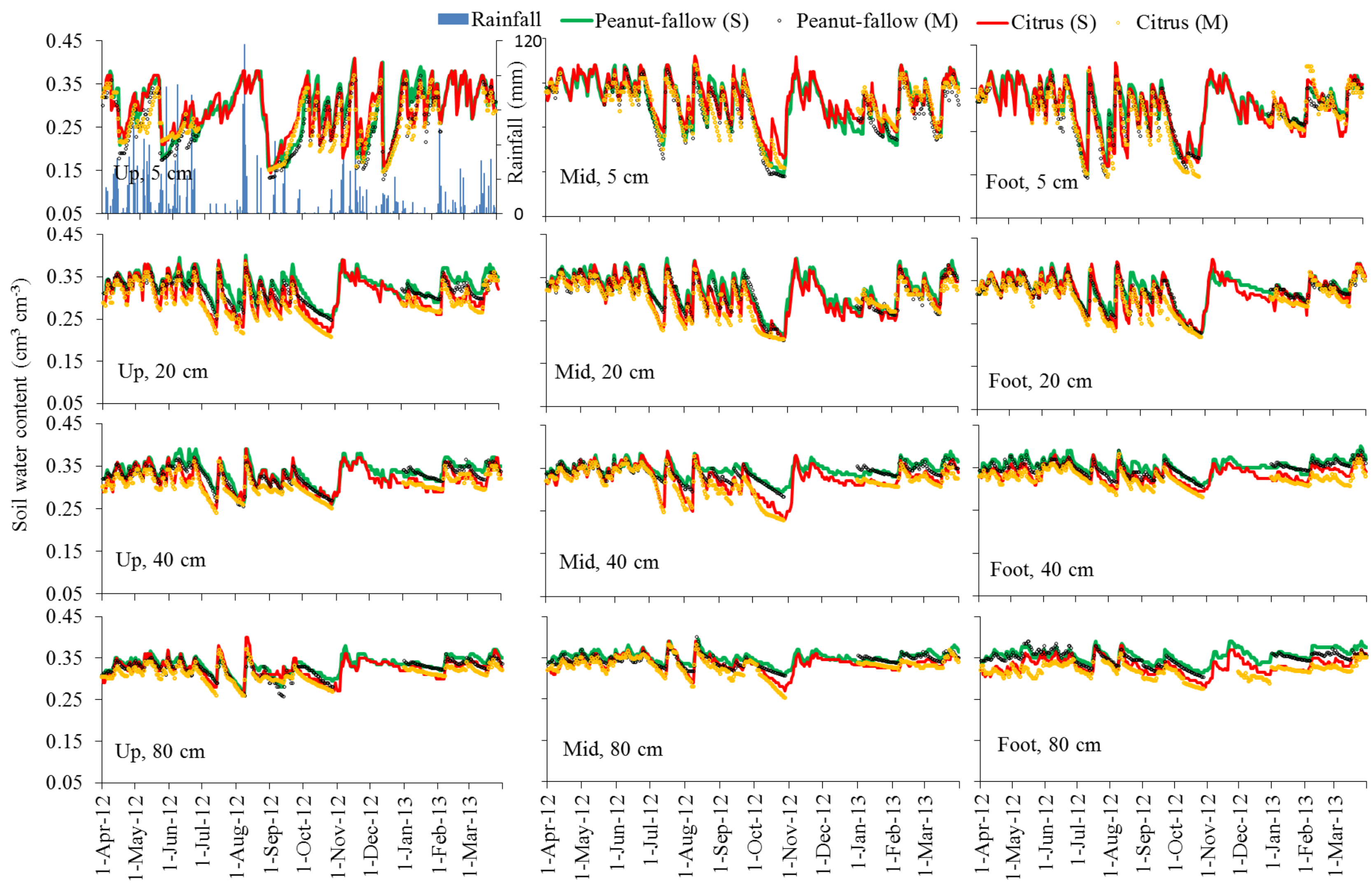

Fig. 3. Daily monitored (M) and HYDRUS-2D simulated (S) soil water content at different depths and slope positions of peanut-follow and citrus land uses during calibration year from Apr. 2012 to Mar. 2013. Up, Mid, and Foot indicate the slope positions.

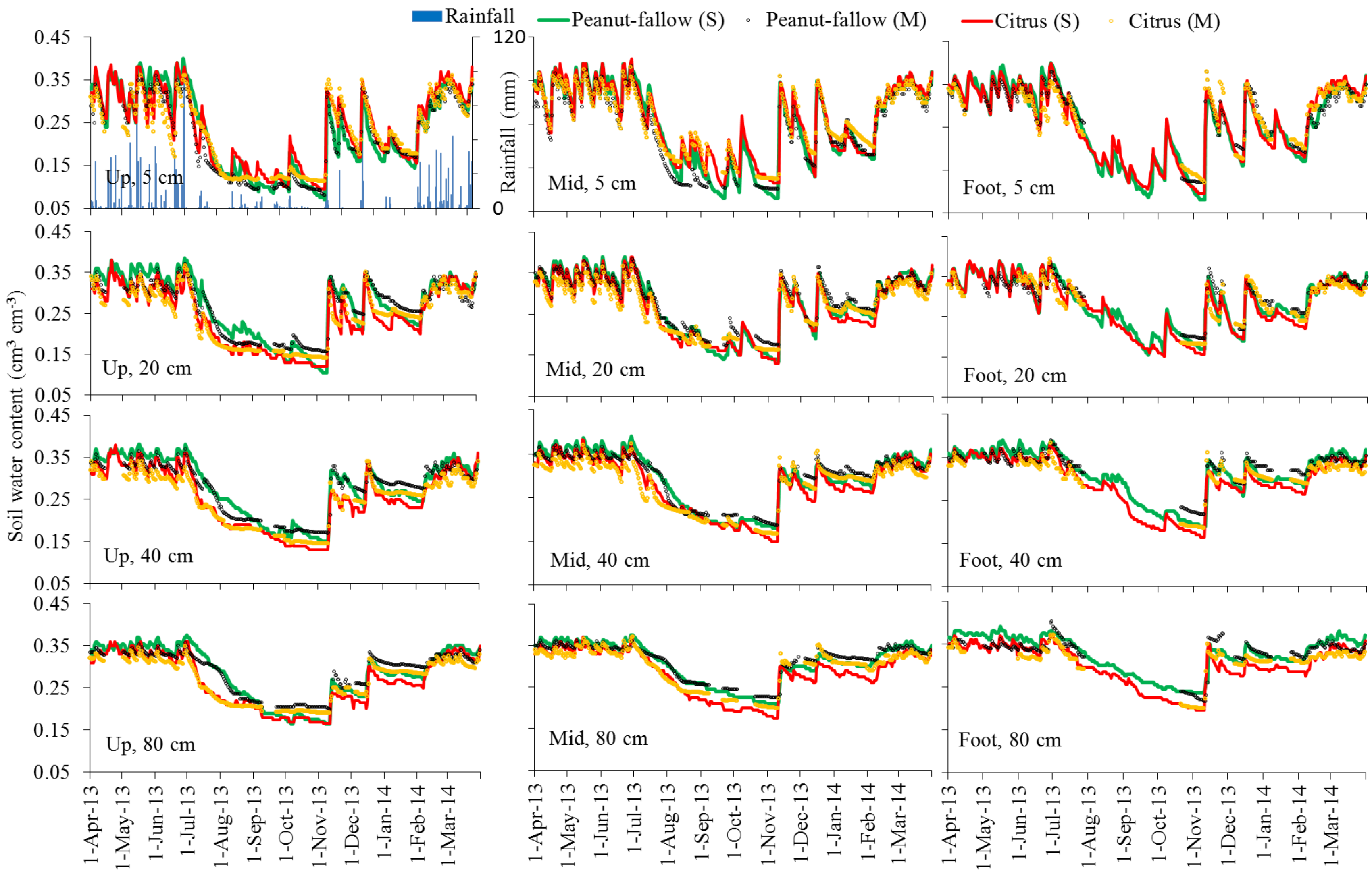

Fig. 4. Daily monitored (M) and HYDRUS-2D simulated (S) soil water content at different depths and slope positions of peanut-follow and citrus plots during validation year from Apr. 2013 to Mar. 2014. Up, Mid, and Foot indicate the slope positions.

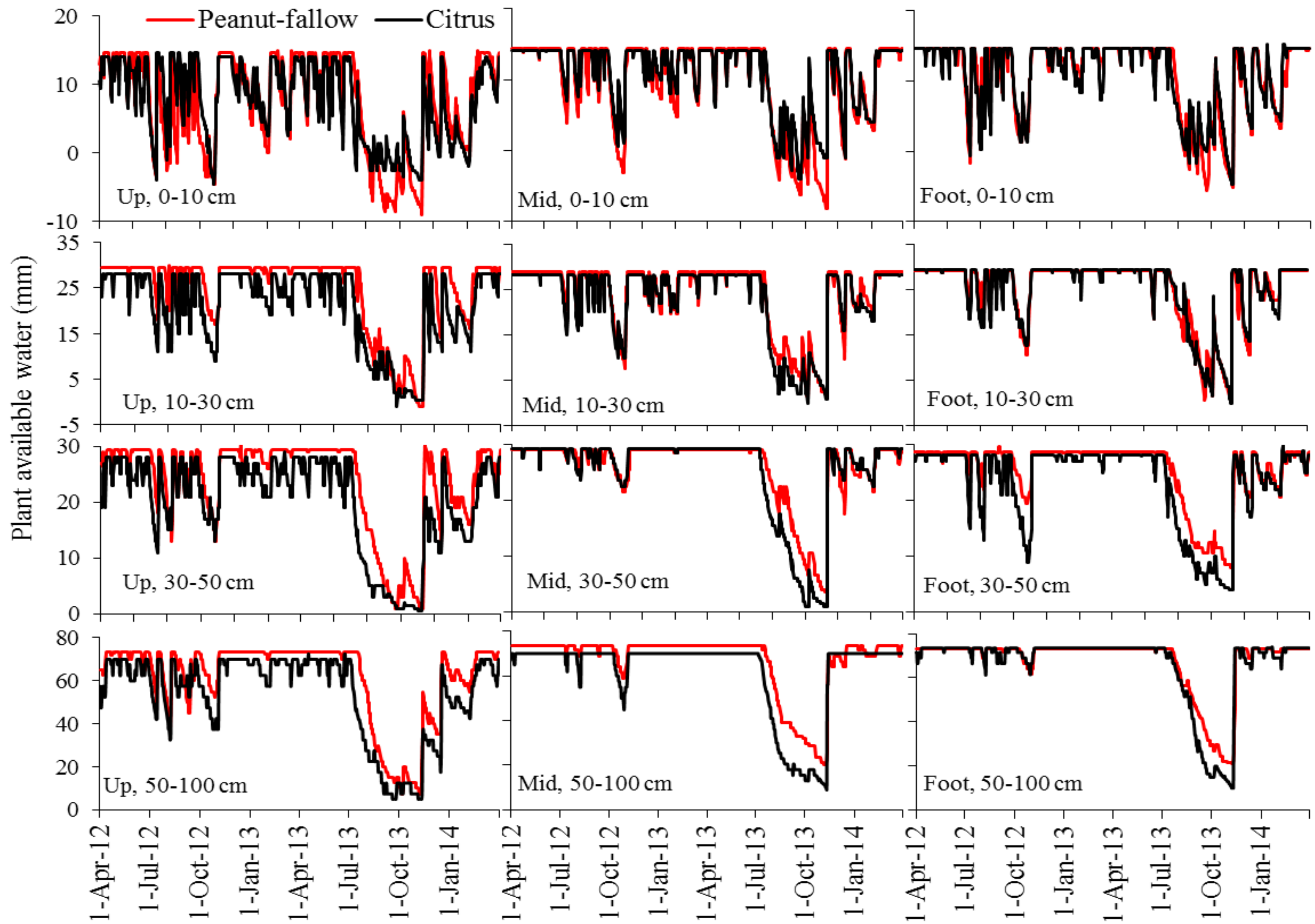

Fig. 5. Dynamics of plant available water (PAW) at different depths of the peanut-fallow and citrus plots. Up, Mid, and Foot indicate the slope positions. Note: Negative values on Y axis indicate the water content below permanent wilting point.

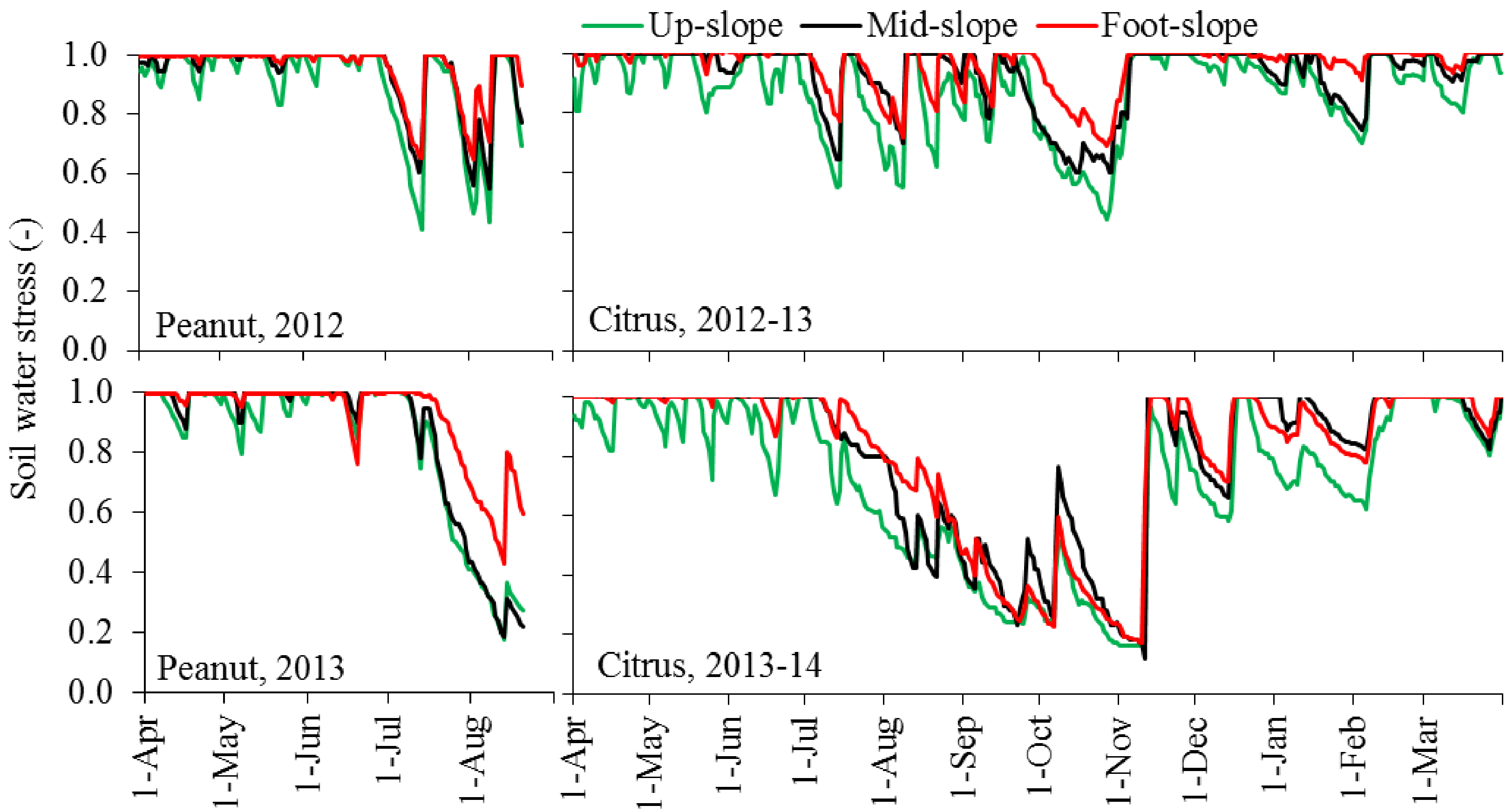

Fig. 6. Changes in soil water stress in the peanut season and citrus plots. The value of stress factor 1 indicates no water stress.