Journal of the Indian Society of Soil Science, Vol. 61, No. 4, pp 300-310 (2013)

Pedo-transfer Functions for Determining Soil Water Retention and Assessing their Utility in Simulation Model for Predicting Rice Growth and Yield

Gouranga Kar*, Sudipta Chattaraj[1] and Ashwani Kumar
Directorate of Water Management, Bhubaneswar, 751023, Odisha

As a case study to determine soil water retention using pedo-transfer functions and assessing their utility in simulation model for predicting rice growth and yield, soil samples were collected at various depths (0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60, 0.60-0.90, 0.90-1.20 m) from 3 locations *viz.*, Satyabadi, Kanas and Dhenkanal of Odisha, representing land ecologies of moderate surface waterlogging (0.5-0.75 m), severe surface waterlogging (>1.0 m) and non-waterlogged upland soils, respectively. The soil texture was clay at all depths at Kanas and Satyabadi whereas, texture of the Dhenkanal soils ranged from sandy clay loam to clay loam. The bulk density was higher in soils of Kanas and Satyabadi while it was low in Dhenkanal. The profile organic carbon stock was higher in waterlogged soils of Kanas and Satyabadi (66.6 and 78.8 Mg ha^{-1}, respectively) than that of Dhenkanal site (59.2 Mg ha^{-1}). Soil moisture retention at field capacity (0.033 MPa) ranged between 0.381 to 0.603 m^3 m^{-3} at Kanas, 0.335 to 0.503 m^3 m^{-3} in Satyabadi and 0.319 to 0.446 m^3 m^{-3} in Dhenkanal at different depths. At permanent wilting point (1.5 MPa), the moisture content varied from 0.185 to 0.262, 0.172 to 0.246 and 0.108 to 0.139 m^3 m^{-3} at Kanas, Satyabadi and Dhenkanal, respectively. Pedo-transfer functions in the form of linear equations were developed for estimating soil water retention at field capacity and wilting point using basic soil properties. These pedo-transfer functions derived soil water constants were used in soil module of DSSAT 4.5 model for predicting rice crop growth and yield. With pedo-transfer derived soil moisture data, the error (%) for maximum LAI was 2.39%, while the error (%) for maximum dry biomass and grain yield were 4.46 and 6.73, respectively. The lower errors indicate that the model predicted crop growth and yield close to the actual values with pedo-transfer derived soil moisture data.

Key words: Soil physical properties, soil moisture retention, hydraulic conductivity, pedo-transfer functions, simulation model

Crop simulation models and their associated decision support system have been used successfully in many countries around the world for evaluating soil-plant-atmosphere relationships and to estimate crop growth and yield (Tsuji *et al*. 1998; Hoogenboom 2000; Jones *et al*. 2003; Bannayan *et al*. 2003). The decision support system for agro-technology transfer (DSSAT) (Jintrawet 1995; Ritchie *et al*. 1998; Tsuji *et al*. 1998; Hoogenboom *et al*. 2004; Sarkar and Kar 2006) is a widely used decision support system which requires daily weather data (maximum and minimum temperature, rainfall, solar radiation), soil data (layer wise physical and chemical properties), genetic coefficients, crop management information to simulate rice crop growth and yield (Kropff *et al*. 2001; Timsina and Connor 2001; Kumar and Sharma 2004; Sarkar and Kar 2006; Timsina and Humphreys 2006). Soil water retention characteristics (SWRC) are the basic requirements for understanding basic soil-plant-water relationship in the simulation model. However, direct measurement of SWRC is time consuming, labour intensive, and expensive. The required instrument, pressure plate apparatus is also not available in most of the laboratories in India to measure the moisture retention at different suction. Soil moisture retention can be estimated satisfactorily by using readily available soil parameters like texture, bulk density, organic matter (Bell and van Keulen 1995; Kar *et al*. 2004; Adhikary *et al*. 2008). Pedo-transfer functions (PTF) in the form of complex methods like artificial

---

*Corresponding author (Email: kar_wtcer@yahoo.com)
Present address
[1] National Bureau of Soil Survey and Land Use Planning, Nagpur, 440 030, Maharastra

natural networks (ANN), nonparametric nearest neighbour were also reported by many authors (Pachepsky *et al*. 1996; Nemes *et al*. 2003; Baker and Ellison 2008). Although, numerous works on PTFs were conducted in many countries still there is a paucity of information on prediction of crop growth and yield through simulation model using these PTFs. The PTF derived soil water retention can be used as input in soil module of simulation model or decision support system for crop growth and yield prediction when actual soil water retention is not available.

In this study, PTFs were developed to derive soil moisture retention using basic soil properties data of three locations of Odisha and the same was validated with the actual field data after determining soil moisture characteristics curves of the site. After validation, the PTFs were used to derive soil moisture retention of the experimental rice field and compared with actual values. Both actual and the PTFs derived soil moisture retention data were used as input in the soil module of DSSAT 4.5 model for predicting growth and yield of rice crop .

Attempt was also made to correlate saturated hydraulic conductivity and porosity with moisture content, texture and bulk density based on the actual field data.

Materials and Methods

Soil Sample Collection

Soil samples were collected after digging profile of 1 m width and 1.2 m depth at 3 locations of Odisha *viz*., Satyabadi, Kanas and Dhenkanal, representing moderate waterlogging, severe waterlogging, and rainfed upland soils of Odisha, respectively. Three soil profiles were dug in each location and results were averaged. The brief information about the study sites are given in table 1.

For determining the saturated hydraulic conductivity and bulk density, the undisturbed soil samples were collected at the depths of 0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60, 0.60-0.90, 0.90-1.20 m with the help of stainless steel core sampler of 5 cm inner diameter and 5.1 cm height. Along with undisturbed core samples, disturbed soil samples were taken from the same depth of the profile for analysis of soil pH, electrical conductivity (EC), texture (% sand, silt and clay) and organic carbon (OC) content. The water content at different suctions *viz*., 0.033 (field capacity), 0.1, 0.3, 0.5, 1.0 and 1.5 MPa (permanent wilting point, PWP) was measured using pressure plate apparatus (Soil Moisture Equipment Corporation, USA) (Klute 1986) to derive soil moisture characteristics curve. Soil texture was determined using Bouyoucos Hydrometer method. Porosity and Particle density were measured as per the standard procedure.

Organic carbon (%) in soil was determined by Walkley and Black (1934) method and the SOC stock of the profile (Mg ha^{-1}) was computed by multiplying the SOC concentration (g kg^{-1}) with the bulk density (Mg m^{-3}), depth (m) and factor by 10. Soil pH and electrical conductivity were determined in 1:2 soil-water suspensions as per the procedure given by Jackson (1973).

Development of Pedo-transfer Functions

Fifty four data sets of basic soil properties like sand, silt, clay and organic matter were used to develop pedo-transfer functions (PTFs) in the form of multiple regression equations using SAS statistical software by considering soil water retention at 0.033 and 0.15 MPa as dependent and basic soil properties as independent variables. A programme in SAS 9.2 package was written using PROC REG command and run using the dependant and independent variables. After running the programme, parameters estimate for intercept and dependant variables, standard error, t-value were recorded and multiple regression equations were developed. The accuracies of the PTFs derived soil water retention were determined based on the values of coefficient of determination (R^2) and RMSE values and compared with actual values. After validating PTFs, these were used to determine soil water retention of the soils of the experimental sites

Table 1. Basic information about the study sites

Information	Site1	Site 2	Site 3
Village	Benakera	Parimandirpur	Parbatia
Block(District)	Satyabadi (Puri)	Kanas (Puri)	Dhenkanal (Dhenkanal)
Agroclimatic zone	Coastal plains of Odisha	Coastal plains of Odisha	Central table top land of Odisha
Land Ecology	Lowland with moderate surface waterlogging (0.5-0.75 m) during rainy season	Lowland with severe surface waterlogging (>1 m) during rainy season	Upland non-waterlogged soils
Cropping system	Rice-Rice	Fellow- Rice	Rice-Vegetables

and utilized as inputs in the soil module of DSSAT 4.5 model to predict the rice crop growth and yield of the experimental plots. The crop growth and productivity predicted by using PTFs derived and actual water retention were compared based on percentage of error between them.

Calibration and Evaluation of the DSSAT Model

The CERES-Rice model embedded in decision support system for agro-technology transfer-DSSAT v4.5 (Jones *et al*. 2003; Hoogenboom *et al*. 2010) was used in this study to validate the pedo-transfer derived soil water constants for predicting rice growth and yield. DSSAT is a physiologically based and management oriented model that utilizes carbon, N, water and energy balance principles' to simulate the growth and development of rice plant. Inputs required for model execution include management practices (plant genetics, plant density, row spacing, transplanting and harvest dates, fertilizer application amounts, dates and method), environmental factors (soil physical and chemical properties *etc*.) and weather conditions (daily minimum and maximum temperature, solar radiation and precipitation). The model was calibrated with the past data obtained in 2008-09 *rabi* season and validated with 2009-10 *rabi* season data on a rice cultivar 'Lalat'. To select the most suitable set of coefficients for each growth and development coefficient an iteractive procedure was used (Hunt *et al*. 1993). During calibration and evaluation process the simulated data for anthesis date, maturity date, grain yield, total biomass and leaf area index were compared with the observed values. A detailed description of the cultivar coefficients for rice variety 'Lalat' used in the model is presented in table 2.

Results and Discussion

Basic Soil Properties of 3 Study Sites

Results of physicochemical properties of the soil samples collected from the three sites of Odisha are presented in table 3(a,b). Average soil sample data of three profiles in each locations indicate that soils were acidic to near neutral in soil reaction as the pH of the soils at different soil depths ranged from 5.8 to 6.8; 6.0 to 6.8; and 5.2 to 6.2 in Satyabadi, Kanas and Dhenkanal, respectively. The EC was low in the upland soils of Dhenkanal, while the salinity levels were comparatively higher in both Satyabadi (0.40-0.90 dS m^{-1}) and Kanas (0.70-0.91 dS m^{-1}). The location of Satyabadi and Kanas was near to coast of the Bay of Bengal which might have led to higher level of salinity as compared to the inland district of Dhenkanal.

The bulk density of Satyabadi and Kanas site was higher *i.e.* above 1.50 Mg m^{-3} in all the depths except at 0-0.15 m, as a result the porosity in both sites is lower than that of Dhenkanal. Among three sites, Dhenkanal had relatively lower bulk density (1.34 to 1.48 Mg m^{-3}) as well as higher porosity (34.4 to 48.7%) as compared to the other two sites. Due to low porosity, the saturated hydraulic conductivity (K_s) was low (0.11 to 0.70 m d^{-1}) at Kanas and Satyabadi except at surface layer (0.397 to 0.415 m d^{-1}). Result showed that owing to higher clay texture, Kanas had 20% less average saturated hydraulic conductivity than that of Satyabadi while the average Ks of upland soils of Dhenkanal was 86 to 89% higher than both the sites of coastal waterlogged plains. Dhenkanal soil had moderate to high K_s values (0.258 to 1.67 m d^{-1}) at different depths of the soil profile. Due to low K_s values, coastal plains of Puri district (Satyabadi and Kanas) possess waterlogging problem. In regard to soil

Table 2. Description of the cultivar coefficients for rice variety 'Lalat

Cultivar trait	Genetic coefficients	Unit	Value
A. Vegetative growth			
1. Time from seed emergence to the end of juvenile phase	P_1	Photo-thermal (day)	126.0
2. Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod	P_2O	(h)	250.0
3. Extent to which phasic development from vegetative to panicle initiation is delayed for each hour increase in photoperiod above P_2O, *i.e.*, 12.5 h	P_2R	Photo-thermal (day)	500.0
B. Reproductive growth			
4. Time starting from grain filling to physical maturity	P_5	Photo-thermal (day)	10.9
5. Maximum spikelet number coefficient	G_1	–	52.0
6. Maximum possible single grain size	G_2	(g)	0.0235
7. Scalar vegetative growth coefficient for tillering relative to IR64	G_3	–	1.03
8. Temperature tolerance scalar coefficient	G_4	–	0.90

Table 3a. Soil physicochemical properties of three sites (S1=Satyabadi, S2 = Kanas, S3 = Dhenkanal)

Site	Soil depth (m)	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})	Porosity (%)	Ks (m d^{-1})	Particle size distribution (%)			Texture class	Soil moisture retention (m^3 m^{-3})	
						Sand	Silt	Clay		FC (0.033 MPa)	PWP (1.5 MPa)
S_1	0-0.15	1.39	2.26	38.6	0.398	34.4	26.0	39.6	C	0.42	0.17
	0.15-0.30	1.61	2.26	29.0	0.014	24.4	11.7	63.9	C	0.50	0.24
	0.30-0.45	1.69	2.27	25.7	0.011	27.7	5.7	66.6	C	0.54	0.27
	0.45-0.60	1.54	1.97	21.9	0.004	22.4	28.0	49.6	C	0.49	0.24
	0.60-0.90	1.56	2.15	27.4	0.055	28.4	24.0	47.6	C	0.40	0.22
	0.90-1.20	1.58	2.43	34.9	0.070	32.1	22.0	45.9	C	0.33	0.24
S_2	0-0.15	1.34	1.68	20.1	0.415	16.4	34.0	49.6	C	0.49	0.23
	0.15-0.30	1.59	1.82	12.6	0.012	10.4	23.3	66.3	C	0.56	0.27
	0.30-0.45	1.54	1.86	17.3	0.013	12.1	23.0	64.9	C	0.58	0.29
	0.45-0.60	1.53	1.88	18.8	0.015	7.1	29.3	63.6	C	0.60	0.29
	0.60-0.90	1.54	1.87	17.5	0.010	14.4	18.7	66.9	C	0.62	0.28
	0.90-1.20	1.38	2.46	43.9	0.267	52.8	7.6	39.6	SC	0.37	0.18
S_3	0-0.15	1.34	2.61	48.7	1.659	50.8	22.6	26.6	SCL	0.33	0.12
	0.15-0.30	1.37	2.15	36.3	0.258	40.4	31.3	28.3	CL	0.38	0.15
	0.30-0.45	1.39	2.34	40.7	0.747	36.4	33.7	29.9	CL	0.40	0.14
	0.45-0.60	1.43	2.29	37.4	0.469	32.4	34.7	32.9	CL	0.45	0.14
	0.60-0.90	1.44	2.27	36.6	1.674	35.4	31.0	33.6	CL	0.40	0.14
	0.90-1.20	1.48	2.26	34.4	0.468	62.2	16.2	21.6	SCL	0.38	0.10

C = Clay, SC = sandy clay, SCL = Sandy clay loam

Table 3b. Soil chemical properties of three sites (S1 = Satyabadi, S2 = Kanas, S3 = Dhenkanal)

Site	Soil depth (m)	pH	EC (dS m^{-1})	Organic carbon (g kg^{-1})	Profile organic carbon stock (Mg ha^{-1})
S_1	0-0.15	6.7	0.90	5.05	10.52
	0.15-0.30	5.8	0.40	5.75	13.88
	0.30-0.45	6.0	0.79	5.05	12.80
	0.45-0.60	6.1	0.80	4.35	10.04
	0.60-0.90	6.1	0.69	3.83	17.92
	0.90-1.20	6.8	0.88	2.26	10.71
S_2	0-0.15	6.2	0.91	4.88	9.80
	0.15-0.30	6.1	0.83	5.05	12.04
	0.30-0.45	6.3	0.87	3.31	7.64
	0.45-0.60	6.0	0.82	4.00	9.18
	0.60-0.90	6.5	0.70	3.66	16.90
	0.90-1.20	6.8	0.86	2.79	12.80
S_3	0-0.15	5.2	0.07	4.00	8.40
	0.15-0.30	5.5	0.06	3.48	7.15
	0.30-0.45	5.8	0.05	3.66	7.64
	0.45-0.60	5.7	0.04	3.48	7.46
	0.60-0.90	6.2	0.07	3.13	13.52
	0.90-1.20	6.1	0.06	3.48	15.45

organic carbon (SOC), the value decreased with the depth in most cases. The SOC content at 0-0.15 m depth was lower (4.0 g kg^{-1}) at Dhenkanal than at Satyabadi (5.75 g kg^{-1}) and Kanas (4.88 g kg^{-1}), respectively. The profile soil organic carbon (PSOC) stock was also determined from the SOC content, bulk density and depth. The PSOC stock within 1.2 m depth was 78.87, 66.96 and 59.26 Mg ha^{-1} at Dhenkanal, Satyabadi and Kanas, respectively.

The soils of coastal waterlogged soils were found to be clay in texture throughout the profile (except at 0.90-1.20 m depth in Kanas which had sandy clay texture). But, Dhenkanal site, representing mid central table land agro-ecological zone and inland districts of Odisha had clay loam texture except at 0-0.15 and 0.90-1.20 m depth (sandy clay loam in texture). The average clay content of the three study sites were found in following order: Kanas (60%) > Satyabadi (52%) > Dhenkanal (29%). Dhenkanal soils had average 45 and 51% less clay content than that of Satyabadi and Kanas, respectively and accordingly the soil moisture retention also varied.

Soil Moisture Retention Characteristics

Moisture content data at 0.033 MPa (FC), 0.1, 0.3, 0.5, 1.0 and 1.5 MPa (PWP) revealed that higher the clay content greater is the moisture retention capacity of the soil. The soil moisture characteristics curves were found to be fit well in power function as given in the figures (Fig. 1a to 1f). The soil moisture retention at FC and PWP are also presented in table 3(a). The higher values of R^2 (>0.90, except at 0.90-1.20 m depth of Dhenkanal) and lower values of standard error of estimate, SEE (0.41 to 2.34) were obtained throughout the profiles in power curve. Soils of Satyabadi and Kanas had 13 and 27% higher moisture content at the lower suction of (0.033 MPa); while at higher suction (1.5 MPa) the moisture retention was 43 and 48% more in Kanas and Satyabadi than that of Dhenkanal. The soil metric suction-moisture content relationship displayed a sharp decrease in moisture content from initially higher to lower values; from 0.033 to 0.1 or 0.3 MPa following a gradual decline till 0.5 MPa; and the change became negligible thereafter. Results indicate the fact that difference in clay content between coastal plain of Puri district and mid central table land of Dhenkanal district might have played crucial role for variation in moisture content throughout the whole suction range. The variation had increased sharply at higher suctions indicating the dominant role of texture at higher suction in retaining soil moisture rather than the structure.

The soil moisture retention at field capacity (FC) and permanent wilting point (PWP) were correlated against clay and sand content (Fig. 2a and 2b), bulk density (Fig. 2c) as well as saturated hydraulic conductivity (Fig. 3a). The relationship was positive when moisture retention was regressed with clay content and bulk density, whereas the slope was negative for porosity and sand. The relation between moisture content at FC and PWP and saturated hydraulic conductivity was also developed (Fig. 3a). The logarithmic regression equations were found to be the best to predict soil moisture retention based on saturated hydraulic conductivity. The logarithmic response curves (Fig. 3a) revealed that at low values of K_s (< 10 m d^{-1}), with slight decline in $K_{s,}$ relatively larger increase in moisture retention at both FC and PWP was observed. The interrelationship between saturated hydraulic conductivity and clay content and bulk density was also established (Fig. 3b and Fig. 3c).

When K_s was regressed with both the clay content (Fig. 3b) and inverse of bulk density (Fig. 3c), the power (R^2 = 0.87, SEE = 13.18) an exponential (R^2 = 0.83, SEE = 17.03) form of regression equations were found to be fitted best for clay and bulk density, respectively. The inverse of bulk density is

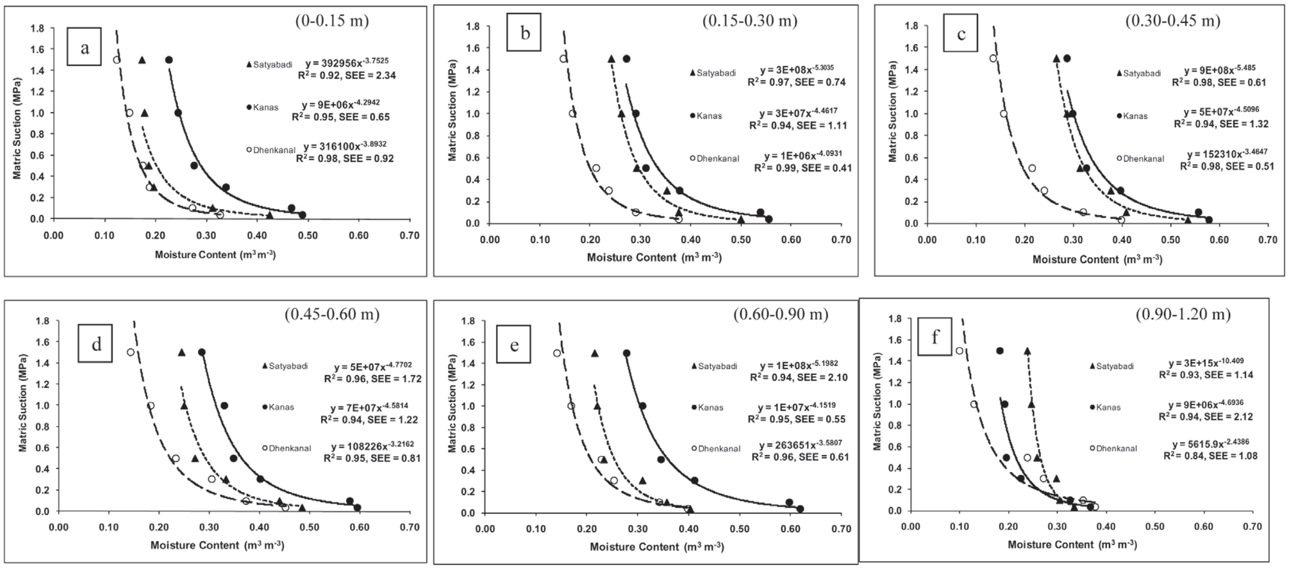

Fig. 1. Soil moisture characteristics curves at six soil depths in the three sites of OdishaInterrelationships between soil hydro-physical parameters and development of pedo-transfer functions

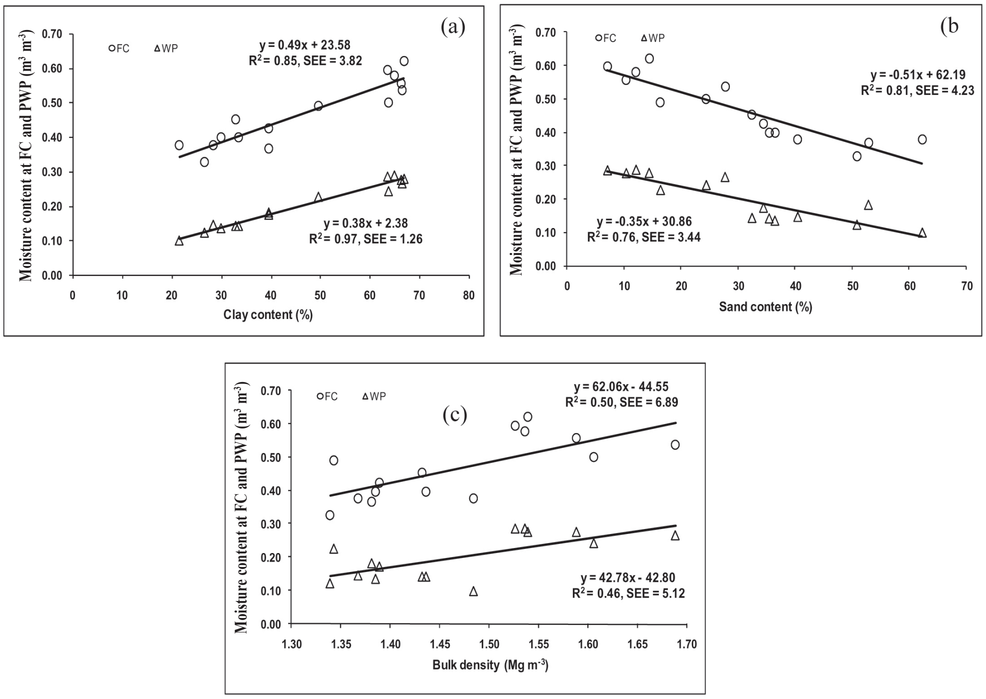

Fig. 2. Moisture content at field capacity and wilting point in relation to clay, sand and bulk density

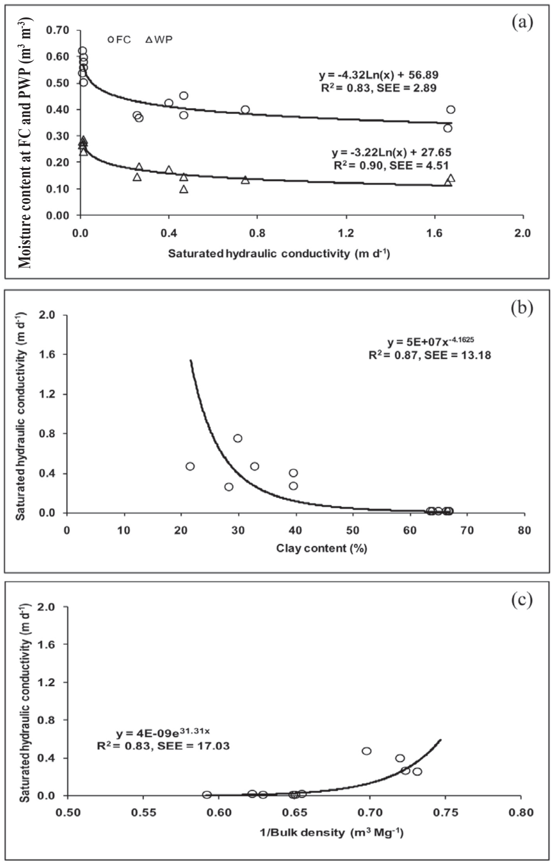

Fig. 3. Saturated hydraulic conductivity in relation to (a) moisture content at field capacity and wilting point (b) clay content and (c) inverse of bulk density as obtained from the measured dataset

an indicator of compaction as well as porosity of soil. The power form of response curve indicate a very low K_s (<10 m d^{-1}) at higher clay content (> 50%) and a sharp increase in K_s in less clay containing (<30%) soil. Similar kind of relation was obtained by Adhikary *et al.* (2008) when K_s was regressed with silt plus clay content and steady infiltration rate with clay content. However, K_s was found to increase exponentially with the increased value of inverse of bulk density. As expected porosity was negatively related with clay content and positively related with sand content. (Fig. 4). Available water capacity (AWC) was also observed to be negatively correlated with porosity.

The pedo-transfer functions in terms of multiple linear regressions were developed to predict moisture estimation (m^3 m^{-3}) at field capacity (θ_{fc}) and wilting point (θ_{PWP}) (Table 4):

$$\theta_{fc} = 0.418 - (0.0058\times sand) + (0.0021\times clay) + (0.0258\times PSOC) \quad \ldots(1)$$

$$\theta_{PWP} = 0.3989 - (0.0039\times sand) - (0.00384\times silt) \quad \ldots(2)$$

$$\theta_{PWP} = 0.0238 + (0.0038\times clay) \quad \ldots(3)$$

The water retention at FC and PWP was derived using above equations and measured versus pedo-transfer derived water retention were presented in fig. 5. The associated statistics *i.e.* R^2, adjusted R^2, MSE (mean sum of error) and RMSE (root of the mean squared error) showed a reasonably good predictive potential of the PTFs to predict soil moisture reten-

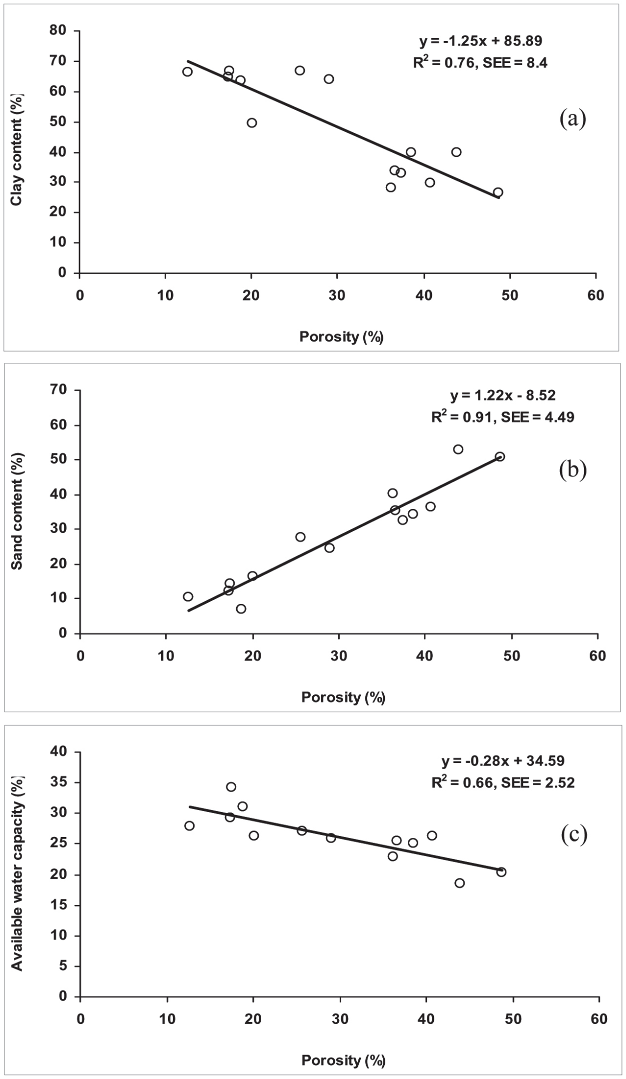

Fig. 4. Variation of porosity in relation to clay, sand and available water capacity (%) from the measured dataset

tion at FC and PWP. However, PTFs to determine moisture retention at PWP (eq. 2) were closer to the observed values than at FC.

Results depicted that water content at higher suction (1.5 MPa) was largely determined by texture (especially that of clay), thus the influence of profile soil organic carbon (PSOC) (aggregation or structure) was minimum (eq. 2 and 3). However, PSOC stock had significant impact on moisture content at field capacity (eq. 1). Similar observations were also made by Rawls *et al*. (2003) and Kar *et al*. (2004).

As the PTFs derived and observed water retention was found closer, attempt was made to derive soil water retention with basic soil data sets of rice experimental field of Alisha, Satyabadi, Puri to predict crop growth and yield of rice under optimum nutrient management using DSSAT 4.5 model. The measured soil properties of experimental field are given in table 5. Using pedo-transfer function (eq. 1 and 2), soil water retention of the experiential plots at FC and PWP were determined and are depicted in fig. 6(a) and fig. 6(b), respectively. Both actual and pedo-transfer derived soil water retention of the experimental field were used as inputs in the soil module of DSSAT 4.5 model for calibration and validation of the model to predict crop growth and yield.

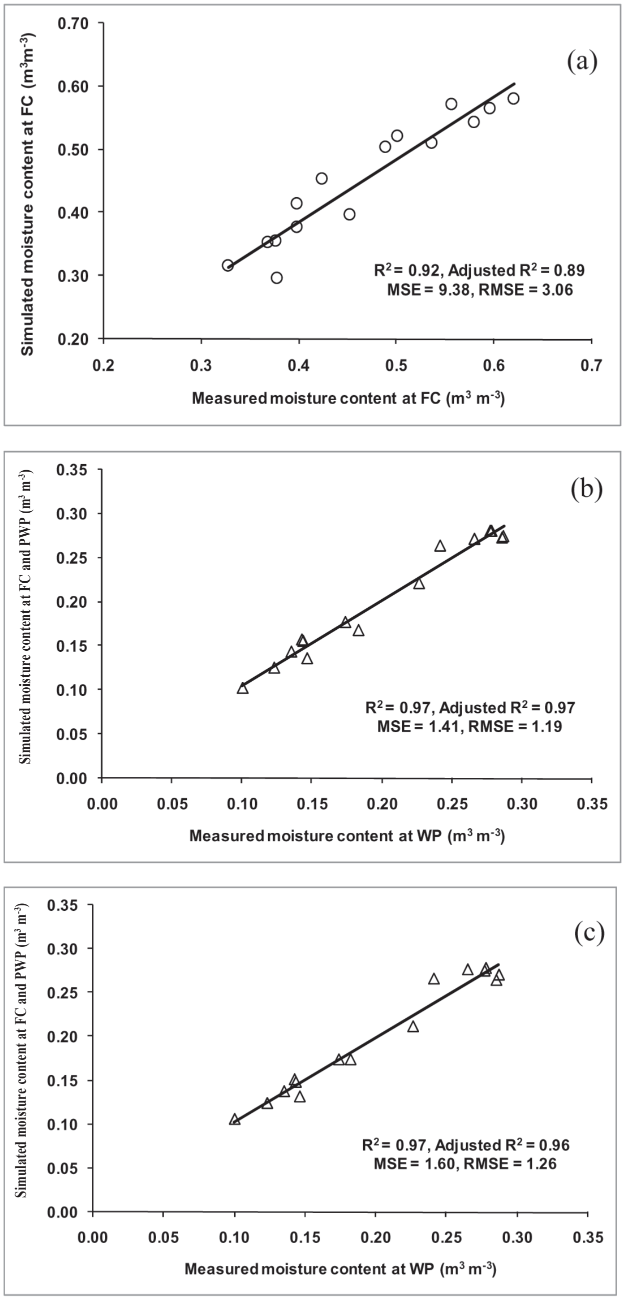

Fig. 5. Predicted versus measured values of moisture content at FC and PWP as derived using the PTFs equations as (a) Eq. 1, (b) Eq. 2 and (c) Eq. 3

Table 4. Regression statistics of pedotransfer functions developed from basic soil dataset of three sites studied (No of observations = 54)

Variables	Parameter estimate	Standard error	t value	Pr > |t|
Volumetric moisture content ($m^3 m^{-3}$) at field capacity				
Intercept	0.4178	6.70	6.23	<.0001
Sand	-0.0058	0.11	-3.04	0.0113
Clay	0.0021	0.11	1.98	0.0433
PSOC	0.0258	3.20	1.43	0.1803
Volumetric moisture content ($m^3 m^{-3}$) at permanent wilting point				
Intercept	0.3989	1.13	35.43	<.0001
Sand	-0.0039	0.02	-20.21	<.0001
Silt	-0.00384	0.03	-9.88	<.0001
Volumetric moisture content ($m^3 m^{-3}$) at permanent wilting point				
Intercept	0.0238	0.96	2.48	0.0274
Clay	0.0038	0.02	19.65	<.0001

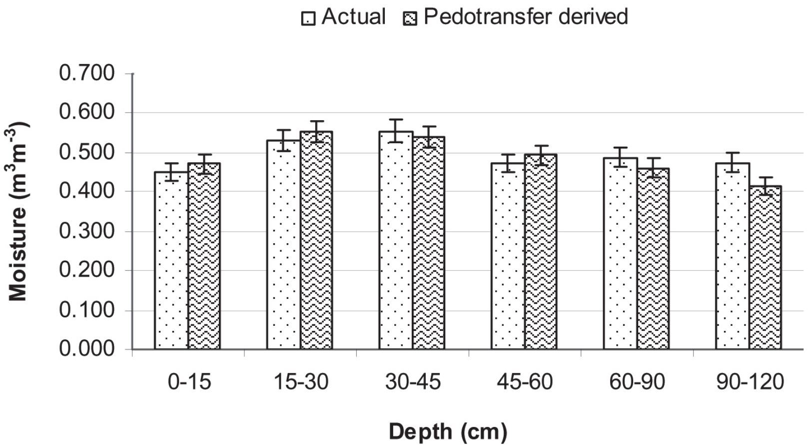

Fig. 6a. PTFs derived versus measured soil moisture content at field capacity of experimental field

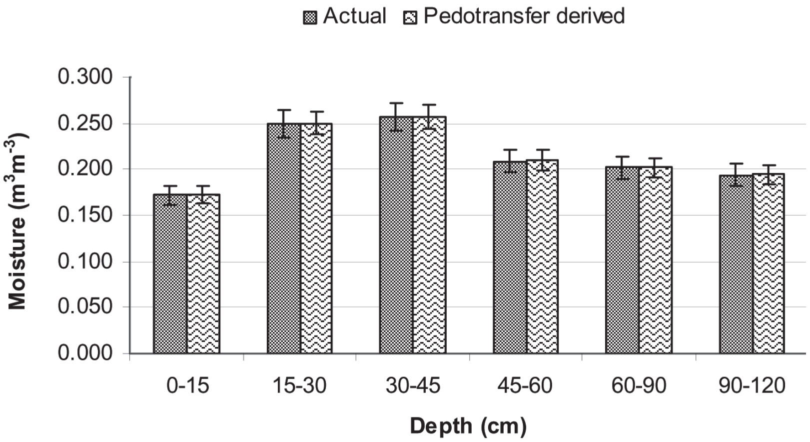

Fig. 6b. PTFs derived versus measured soil moisture content at permanent wilting point of experimental field

Calibration of DSSAT Model

The DSSAT model was calibrated with experimental data collected during the 2008-09 rice crop season using derived cultivar coefficients for 'Lalat' cultivar that determine vegetative (P_1, P_2O, and P_2R) and reproductive (P_5, G_1, G_2, G_3 and G_4) growth and development. During calibration, a close agreement was obtained between observed and simulated values for rice phenology. The model predicted the dates from transplanting to anthesis and transplanting to maturity with a difference of 2 days between observed and simulated dates for rice cultivar 'Lalat' (Table 6).

Table 5. Measured soil profile data of the experimental field utilized as input of DSSAT 4.5 model for calibration and validation

Soil parameters	Soil profile depth (m)					
	0-0.15	0.15-0.30	0.30-0.45	0.45-0.60	0.60-0.90	0.90-1.20
Lower limit ($m^3 m^{-3}$) of soil moisture	0.193	0.232	0.254	0.235	0.211	0.223
Upper limit, drained ($m^3 m^{-3}$) of soil moisture	0.452	0.532	0.555	0.472	0.488	0.448
Upper limit, saturated ($m^3 m^{-3}$) of soil moisture	0.586	0.637	0.641	0.594	0.592	0.554
Root growth factor (0-1)	1.000	1.000	0.607	0.497	0.368	0.172
Sat. Hydraulic conductivity, macropore (cm h^{-1})	39.3	3.24	7.87	1.63	1.63	1.63
Bulk density (Mg m^{-3})	1.45	1.54	1.59	1.54	1.57	1.61
Organic carbon (g kg^{-1})	6.11	5.01	5.25	4.95	3.85	3.12
Clay (<0.002 mm) (%)	41.6	61.6	63.5	51.2	49.2	47.2
Silt (0.05-0.002) (%)	25.4	17.1	11.3	21.2	23.3	21.2
pH	6.8	6.8	6.2	6.3	6.4	6.5

Table 6. Calibrated results of rice growth and yield using actual soil water retention data in DSSAT 4.5 model during 2008-09

Transplanting date	Phenology	Simulated	Observed	Error (%)
05 December 2008	Anthesis date (date after transplanting)	71	73	-2.74
	Maturity date (date after transplanting)	102	104	-1.92
	Growth and yield			
	Maximum LAI	5.45	5.75	-5.22
	Maximum top dry biomass (kg ha^{-1})	12850	13450	-4.46
	Grain yield (t ha^{-1})	4.95	5.1	-2.97

The simulated and observed values were in good agreement for LAI and total above-ground biomass at different phenological stages. The lower values for error (-5.22 and -4.46%, respectively) reflected that the model predicted LAI and above-ground biomass were close to the observed values. At final harvest, the simulated grain yield was also in good agreement with the observed values and the error was only 2.97% for the grain yield. The lower percentage of error between simulated and observed LAI and dry biomass shows the ability of model to simulate rice growth and development under irrigated conditions for tropical monsoon climate of eastern India.

Model Evaluation

The CSM-CERES-Rice model was evaluated with the experimental data collected during the 2009-10 and run with both the actual and pedo-transfer derived water retention values (Table 7a and 7b). A perfect match was obtained between the observed and

Table 7a. Validated rice growth and yield using actual soil water retention data in DSSAT 4.5 model during 2009-10

Transplanting date	Phenology	Simulated	Observed	Error (%)
04 December 2009	Anthesis date (date after transplanting)	70	72	-2.78
	Maturity date (date after transplanting)	103	104	-0.96
	Growth and yield			
	Maximum LAI	5.71	5.95	-4.03
	Maximum top dry biomass (kg ha^{-1})	12840	13120	-2.13
	Grain yield (t ha^{-1})	4.85	5.1	-4.90

Table 7b. Validated rice growth and yield using pedo-transfer derived soil water retention data in DSSAT 4.5 model during 2009-10

Transplanting date	Phenology	Simulated	Observed	Error (%)
04 December 2009	Anthesis date (date after transplanting)	70	73	-4.11
	Maturity date (date after transplanting)	103	105	-1.90
	Growth and yield			
	Maximum LAI	5.71	5.85	-2.39
	Maximum top dry biomass (kg ha^{-1})	12840	13440	-4.46
	Grain yield (t ha^{-1})	4.85	5.2	-6.73

simulated values for rice phenology both with actual and pedo-transfer derived water retention. The model predicted the dates from transplanting to anthesis with 2 (two) difference dates and transplanting to maturity with 1 (one) day difference between the observed and simulated dates when actual water retention value was taken with error of -2.78% and -0.96%, respectively (Table 7a). With prod-transfer derived soil water retention the difference of observed and simulated anthesis date was 3 days with the error of -4.11%. The simulated and observed values for leaf area index (LAI) and total above-ground biomass at different phenological stages were in good agreement. With actual soil moisture data, the error (%) for LAI was 4.03%, while the error for total biomass and grain yield was -2.13 and -4.90%, respectively (Table 7, a). With pedo-transfer derived soil moisture data, the lower error (%) for maximum LAI was -2.39%, while the error (%) for maximum dry biomass and grain yield were -4.46 and -6.73, respectively. The lower errors indicate that the model predicted LAI and above-ground biomass closely. In general, the results for model evaluation with the observed data sets indicate that the DSSAT 4.5 model was able to simulate yield accurately for transplanted rice with pedo-transfer derived soil water retention as well.

Conclusions

In this study, pedo-transfer functions in the form of linear regressions were derived using soil profile data of three locations of Odisha. The soil water constants were derived using PTFs and used as inputs in the soil module of DSSAT 4.5 model for predicting growth and yield of rice crop. The soil organic carbon stock plays significant role in lower suction range. The lower error (%) indicates that the predicted LAI and above-ground biomass by the model was matched quite well with the observed values. In general, the results for model evaluation with the observed data sets indicated that the DSSAT 4.5 model was able to simulate yield accurately for transplanted rice with pedo-transfer derived soil water retention as well.

References

Adhikary, P.P., Chakraborty, D., Kalra, N., Sachdev, C.B., Patra, A.K., Kumar, S., Tomar, R.K., Chandna, P., Raghav, D., Agarwal, K. and Sehgal, M. (2008) Pedotransfer functions for predicting the hydraulic properties of Indian soils. *Australian Journal of Soil Research,* **46**, 476-484.

Baker, L. and Ellison, D. (2008) Optimisation of pedotransfer functions using an artificial neural network ensemble method. *Geoderma* **144**, 212-224

Bannayan, M., Crout, N. M. J. and Hoogenboom, G. (2003) Application of the CERES-wheat model for within season prediction of winter wheat yield in the United Kingdom. *Agronomy Journal,* **95**, 114-125.

Bell, A.M. and van Keulen, H. (1995) Soil pedotransfer functions for four Mexican soils. *Soil Science Society of America Journal* **59**, 865-871.

Hunt, L.A., Pararajasingham, S., Jones, J.W., Hoogenboom, G., Imamura, D.T. and Ogoshi, R.M. (1993) GENCALC: Software to facilitate the use of crop models for analyzing field experiments. *Agronomy Journal* **85**, 1090-1094.

Hoogenboom, G. (2000) Contribution of agro-meteorology to the simulation of crop production and its applications. *Agriculture and Forest Meteorology* **103**, 137-157.

Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Batchelor, W. D., Hunt, L. A., Boote, K.J., Singh, U., Uryasev, O., Bowen, W.T., Gijsman, A.J., du Toit, A., White, J.W. and Tsuji, G.Y. (2004) *Decision support system for agro-technology transfer (DSSAT) version 4.0*. Honolulu: University of Hawaii, CD-ROM.

Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K.J., Hunt, L. A., Singh, U., Lizaso, J.L., White, J.W., Uryasev, O., Royce, F.S., Ogoshi, R., Gijman, A.J. and Tsuji, G.Y. (2010) *Decision support system for agrotechnology transfer, (DSSAT) version 4.5*. Honolulu: University of Hawaii, CD-ROM.

Jackson, J.L. (1973) *Soil Chemical Analysis*. Prentice Hall of India Pvt. Ltd., New Delhi.

Jintrawet, A., (1995) A decision support system for rapid assessment of lowland rice-based cropping alternatives in Thailand. *Agricultural System* **47**, 245-258.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A. (2003) The DSSAT cropping system model. *European Journal of Agronomy*, **18**, 235-265.

Kar, G., Singh, R.and Verma, H.N., (2004) Spatial variability studies of soil hydro-physical properties using GIS for sustainable crop planning of a watershed of eastern India and its testing in a rainfed rice area. *Australian Journal of Soil Research* **42**, 369-379.

Klute, A. (1986) Water retention: laboratory methods. In *Methods of Soil Analysis Part-I* (A. Klute, Eds.), pp. 635-662, ASA, Monograph, Madison, Wisconsin, USA.

Kropff, M.J., Bouma, J., and Jones, J. W. (2001) Systems approaches for the design of sustainable agroecosystems. *Agricultural System* **70**, 369-393.

Kumar, R., and Sharma, H.L. (2004) Simulation and validation of CERES-Rice (DSSAT) model in northwestern Himalayas. *Indian Journal of Agricultural Sciences* **74**, 133-137.

Nemes, A., Schaap, M.G., Wosten, J.H.M. (2003) Functional Evaluation of Pedotransfer Functions Derived from Different Scales of Data Collection. *Soil Science Society of America Journal* **67**, 1093-1102.

Pachepsky, Y.A., Timlin, D. and Varallyay, G. (1996) Artificial neural networks to estimate soil water retention from easily measurable data. *Soil Science Society of America Journal* **60**, 727-733.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M. and Bloodworth, H. (2003) Effect of soil organic carbon on soil water retention. *Geoderma* **116**, 61-76.

Ritchie, J.T., Singh, U., Godwin, D.C., and Bowen, W.T. (1998) Cereal growth, development and yield. In *Understanding options for agricultural production* (G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton Eds.), pp. 79-98, Dordrecht: Kluwer Academic.

Sarkar, R. and Kar, S. (2006) Evaluation of management strategies for sustainable rice-wheat cropping system, using DSSAT seasonal analysis. *Journal of Agricultural Sciences* **144**, 421-434.

Timsina, J. and Connor, D.J. (2001) Productivity and management of rice-wheat cropping systems: Issues and challenges. *Field Crops Research* **69**, 93-132.

Timsina, J., and Humphreys, E. (2006) Performance of CERES-rice and CERES-wheat models in rice-wheat systems: A review. *Agricultural System* **90**, 5-31.

Tsuji, G.Y., Hoogenboom G. and Thornton, P.K. (1998) *Understanding options of agricultural production*. Dordrecht, The Netherlands: Kluwer Academic Publishers and International Consortium for Agricultural Systems Applications.

Walkley, A. and Black, I.A. (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29-38.

Received 31 December 2012; Received in revised form 25 September 2013; Accepted 22 November 2013