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A modelling approach to evaluate the long-term effect of soil texture on spring wheat productivity under a rain-fed condition

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Soil surface texture is an important environmental factor that influences crop productivity because of its direct effect on soil water and complex interactions with other environmental factors. Using 30-year data, an agricultural system model (DSSAT-CERES-Wheat) was calibrated and validated. After validation, the modelled yield and water use (WU) of spring wheat (*Triticum aestivum L.*) from two soil textures (silt loam and clay) under rain-fed condition were analyzed. Regression analysis showed that wheat grown in silt loam soil is more sensitive to WU than wheat grown in clay soil, indicating that the wheat grown in clay soil has higher drought tolerance than that grown in silt loam. Yield variation can be explained by WU other than by precipitation use (PU). These results demonstrated that the DSSAT-CERES-Wheat model can be used to evaluate the WU of different soil textures and assess the feasibility of wheat production under various conditions. These outcomes can improve our understanding of the long-term effect of soil texture on spring wheat productivity in rain-fed condition.

Understanding of the variable response of crop to the environment is vital to crop management in agricultural systems. Available growing season precipitation is the most influential factor[1], to the productivity of spring wheat (*Triticum aestivum* L.) in the semiarid Canadian prairies. Productivity is also influenced by other environmental and management factors, including temperature, fertilizer rate, crop rotation, tillage, and cultivar[2–4].

The soil texture is another factor that influences wheat productivity because of its significant influence on ecological and hydrological processes, such as water retention, ion exchange and nutrient cycling[5–7]. The study of soil texture effects under field conditions is challenging using short-term data and classical statistics because of confounding effects of factors in the field, such as precipitation, that interact with soil texture effects. For example, conflicting effects of texture were found by Turner *et al.* (2004)[8] under a rain-fed growing condition. They found that the proportion of soil clay content has either a positive or negative effect on the water use efficiency (WUE) of wheat. This confusing result could be caused by many confounding factors acting together to reverse the soil texture effect on WUE depending on exact growing conditions.

Agricultural system simulation models that capture current knowledge of agricultural science have the potential to elucidate the effect of soil textures on crop productivity and water use (WU). Agricultural system simulation models, such as DSSAT (Decision Support System for Agrotechnology Transfer) Crop System Models, are often used as tools to estimate the environmental impacts on field crop production. A number of previous studies have used DSSAT-CERES to discern various influences on crop productivity, such as temperature[9], irrigation[10,11], nitrogen cycling[12], tillage[13], and crop rotation[14]. However, there are few studies in the literature[15] that investigate the effect of soil texture, another important factor influencing spring wheat productivity. Our previous study[16] simulated the crop productivity in different soil textures but predominantly focused on climate effect on seeding dates. Therefore, there is a need to evaluate the capability of DSSAT-CERES-Wheat model to simulate the effect of soil texture on crop productivity. It is also essential to demonstrate if DSSAT-CERES-Wheat model can be used to estimate the WU difference caused by soil texture.

Table 1 | Growing season (May to August) precipitation (GSP, mm), nutrients applied, grain yield and biomass of wheat grown in silt loam and clay soil from 1982 to 2011

Year	GSP (mm)	Nutrients applied (NO_3-N kg ha^{-1})		Grain yield (kg ha^{-1})		Biomass (kg ha^{-1})	
		Silt loam	Clay	Silt loam	Clay	Silt loam	Clay
1982	243	62	43	2839 (245)	1577 (63)	8443 (837)	3791 (216)
1983	186	55	55	2111 (56)	-	5355 (208)	-
1984	94	50	55	651 (154)	1166 (181)	1933 (353)	3062 (450)
1985	73	35	25	764 (146)	1156 (197)	1999 (158)	2552 (378)
1986	205	20	20	2873 (237)	-	6751 (551)	-
1987	129	45	45	1399 (161)	783 (124)	2796 (366)	1450 (251)
1988	143	38	5	532 (83)	-	1288 (176)	-
1989	210	19	23	2258 (157)	1663 (181)	6216 (201)	4881 (449)
1990	179	45	32	2485 (62)	2159 (150)	6153 (138)	5240 (486)
1991	302	55	55	2770 (275)	3052 (45)	7827 (627)	8669 (561)
1992	183	58	60	1866 (56)	2017 (28)	5240 (98)	4817 (54)
1993	175	60	55	2430 (97)	2783 (331)	5950 (208)	7167 (575)
1994	160	54	58	2384 (149)	2518 (340)	7553 (600)	6363 (859)
1995	189	61	64	2809 (313)	2499 (427)	8069 (706)	7459 (1264)
1996	168	53	60	2320 (175)	2276 (111)	6331 (695)	6263 (114)
1997	163	58	62	2775 (432)	2511 (148)	6689 (813)	6581 (394)
1998	166	64	63	1072 (171)	1337 (53)	4220 (427)	4041 (157)
1999	240	49	62	2416 (186)	3234 (256)	6395 (707)	7966 (817)
2000	245	65	66	2035 (54)	1962 (488)	6386 (310)	5415 (814)
2001	112	63	64	970 (255)	663 (101)	2072 (588)	1402 (216)
2002	237	32	25	2354 (388)	2100 (307)	5463 (806)	4643 (731)
2003	129	60	51	1675 (227)	2145 (152)	5048 (773)	4999 (394)
2004	211	46	46	3009 (83)	2690 (61)	7668 (147)	7305 (486)
2005	167	60	56	2273 (263)	2948 (205)	6566 (247)	8111 (422)
2006	269	58	60	1661 (196)	2037 (149)	4550 (377)	5620 (329)
2007	110	61	65	1264 (129)	2193 (138)	3482 (403)	5476 (596)
2008	253	40	55	2176 (260)	2970 (265)	4860 (736)	8428 (655)
2009	94	55	57	1374 (193)	2278 (215)	2782 (378)	4760 (454)
2010	286	49	54	2472 (282)	2932 (416)	6346 (780)	6997 (905)
2011	240	55	57	2880 (492)	2638 (156)	7478 (1241)	6387 (405)
Mean	185	51	49	2030	2159	5397	5352

Note: Values in parentheses are the standard deviation. '-' is missing value.

Our objectives were to: 1) calibrate the DSSAT-CERES-Wheat model for simulation of wheat productivity in two soil textures (silt loam and clay soil); 2) validate the calibrated model by comparing simulated and measured wheat productivity and soil moisture data; and 3) compare the estimated water use (WU) difference between these two soil textures from the simulation results.

Methods

Study sties and experimental set-up. The study was conducted at two sites with contrasting soil texture that are located in the drier portion of the Canadian prairies[17]. The sites are about 30 km apart. These sites are located at southwest Saskatchewan, Canada on Brown chernozem soils[18]. The land was slightly sloping (0.5 to 2%). The annual average temperature and total precipitation near here is 6.9°C and 332 mm, respectively[16]. Precipitation during the summer and fall periods was usually in the form of rain, most of which evapotranspires, but some penetrates to deeper soil layers. During the winter, the precipitation was usually in the form of snow that lies on the frozen soil until March or April when it melts. Much of this snowmelt runs off and is lost to wheat production[19].

The data used in this study was from a long-term tillage experiment and only data for the conventional tillage treatment was used. The experiment established on a silt loam site (Swift Current, 50.288°N, 107.794°W) and a clay soil site (Stewart Valley, (50.596°N, 107.805°W). Randomized complete block designs were used, with four replications on the silt loam site, and three replications on the clay site.

Management (tillage, fertilizer rate, etc.) was as consistent as possible between the two sites. The same wheat varieties that have similar phenology and yield performance were sown at both locations each year. A tillage operation occurred just prior to

Table 2 | Selected soil physical properties at the slit loam and clay sites

Soil Textures	Soil profile depth (cm)	0–15	15–30	30–60	60–90	90–120
Silt loam	SLLL	0.12	0.11	0.10	0.09	0.09
	SDUL	0.29	0.29	0.27	0.27	0.25
	SSAT	0.47	0.47	0.47	0.47	0.47
	Root growth factor	1.00	0.95	0.82	0.47	0.26
	SSKS	1.42	2.76	4.32	3.04	3.04
	Clay content (%)	18.2	24.2	25.4	33.4	31.7
	Silt content (%)	50.4	49.4	33.4	25.9	27.9
Clay	SLLL	0.14	0.14	0.16	0.18	0.20
	SDUL	0.47	0.47	0.47	0.47	0.47
	SSAT	0.55	0.55	0.55	0.55	0.51
	Root growth factor	1.00	0.95	0.82	0.47	0.26
	SSKS	0.33	0.33	0.33	0.33	0.22
	Clay content (%)	59	59	59	59	69
	Silt content (%)	36	36	36	36	28

Table 3 | Cultivar parameters and part ecotype parameters for wheat developed for simulation using the DSSAT-CERES-Wheat module

Parameters	Definitions	Calibrated values
P1V	Days at optimum vernalizing temperature required to complete vernalization	30
P1D	Percentage reduction in development rate in a photoperiod 10 hour shorter than the threshold relative to that at the threshold	55
P5	Grain filling (excluding lag) phase duration (°C.d)	490
G1	Kernel number per unit canopy weight at anthesis (#/g)	15
G2	Standard kernel size under optimum conditions (mg)	33
G3	Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g)	0.8
PHINT	Interval between successive leaf tip appearances (°C.d)	75
HSTD	Standard canopy height (cm)	95
LAWR2	Lamina area to weight ratio, phase 2 (cm^2/g)	140
LAWRS	Lamina area to weight ratio of standard first leaf (cm^2/g)	200
P1	Duration of phase end juvenile to double ridges (PVTU)	240
P1DPE	Day length factor, pre emergence (#,0–1)	0.0
P2	Duration of phase double ridges to end leaf growth (TU)	180
P3	Duration of phase end leaf growth to end spike growth (TU)	160
P4	Duration of phase end spike growth to end grain fill lag (TU)	400
P4SGE	Stem growth end stage (Growth Stage)	4.45
TBGF	Temperature base, grain filling (°C)	0.0
PARUR	PAR conversion to dry material ratio, after last leaf stage (g/MJ)	2.5
PARUV	PAR conversion to dry material ratio, before last leaf stage (g/MJ)	2.2
WFGU	Water stress factor, growth, upper (fr)	1.0
WFPGU	Water factor, genotype sensitivity to stress when grain filling (0–1)	0.8
WFPU	Water stress factor, photosynthesis, upper (fr)	1.0

seeding, usually a day or two before the seeding operation. Tillage depth was approximately 5 cm. In-crop herbicide application normally occurred in early to mid-June, around the 5 to 6 leaf stage of the crop. Details of the fertilizer management on these two sites have been reported previously[15,19,20]; consequently, only that pertinent to this study are presented. The fertilizer rates of the two sites were quite similar (Table 1). Grain yield and above ground biomass (Table 1) were determined at full ripeness. Total aboveground yield and grain yield from a 1 m^2 equivalent area were measured after air drying of the samples. A minimum of three samples were taken per plot for most measurements. Soil moisture was measured each year after harvest. Three 2.5-cm diameter cores were taken per plot with a truck-mounted hydraulic soil sampler. Gravimetric soil water content were determined for the 0–15, 15–30, 30–60, 60–90 and 90–120 cm depths and these values converted to volumetric basis using bulk densities.

Model modification of seedling emergence. The timing of seedling emergence greatly affects the growth and yield of wheat. The DSSAT-CSM is used worldwide for many different applications, but its simulation of the timing of seedling emergence of wheat is not satisfactory under certain circumstances[21]. The cereal crop seedling emergence is simulated by DSSAT-CSM model using thermal time and adjusted by a soil water factor, assuming that the adjusted thermal time is linearly related to the emergence process[22]. However, Jame and Cutforth (2004)[21] showed that the response of emergence to temperature is not linear. In order to improve the prediction of seedling emergence, we incorporated a newly developed non-linear model, the Beta model, into DSSAT-CSM. For a more detailed description, please refer to Wang *et al.* (2009)[23].

Model input. The model requires daily weather data including maximum and minimum temperature and precipitation that were obtained from the Meteorological Service of Canada (MSC). The latter Daily solar radiation was calculated using the Mountain Climate Simulator[24]. The model also requires input parameters describing crop and soil characteristics. The soil parameters included lower soil water limit (LL, $cm^3\ cm^{-3}$), upper drainage limit (DUL, $cm^3\ cm^{-3}$), upper soil water limit (SAT, $cm^3\ cm^{-3}$), soil organic C content (wt.%), dry bulk density (g cm^{-3}), saturated hydraulic conductivity, soil pH, clay and silt content. The pH, clay and silt data were obtained from Saskatchewan Soil Survey reports. The soil hydraulic parameters (LL, DUL and SAT) were obtained by a soil texture based pedo-transfer function (the SPAW model) developed by Saxton and Rawls (2006)[25]. The root distribution parameter was estimated by a method provided by Gijsman *et al.* (2007)[26]. The data were used to construct the model soil profiles (Table 2).

The soil moisture was simulated by the DSSAT model. Since historic soil water content before experiment initiation was unknown, the model was initialized to start three years prior to the period of analysis. A spin-up period of three years was found to be adequate for the soil water values to stabilize and not be affected by the initial input values[16]. Once the soil profile initial conditions were established, the simulations were run from 1982 to 2011.

Crop management data needed are seeding date, seeding depth, row spacing, and plant population.

Model calibration. The method for calibrating parameters (soil, ecotype and cultivar) of the crop models is a step-by-step procedure following the approach recommended by Boote[27] of calibrating soil moisture first, followed by phenology, and then yield (biomass and grain yield). The initial soil hydraulic parameters were obtained by a soil texture based model (SWAP[25]). Plant parameters (ecotype and cultivar) from a previous study[23] conducted in the same area and using same cultivar as our study were used as initial values for calibration. Model calibration used part (1982–1999) of the long-term data of the two soil textures (sites) and two (2004 and 2005) of the three years of data from a physiological study. A single set of ecotype and cultivar parameters was used since the cultivars grown from 1982 to 2011 have similar phenology and yield performance (Table 3). For the calibration, we fixed the maximum possible seed weight under non-stressed conditions at 33 g, the highest value reported by Wang *et al.* (2002)[28] using the same cultivar in our site. As little information on the other cultivar and ecotype parameters was available in the experiments or literature, they were mostly calibrated through trial and error to match simulations with measurements.

Statistics for model calibration and validation. The inaccuracies in each simulation step will affect the accuracy of simulated results for the subsequent simulation step. These inaccuracies will add together across all simulation steps and affect final estimated results. Also, the inaccuracies of simulated soil moisture will affect the accuracy of the phenology simulation. Finally, inaccuracies in soil moisture and

Table 4 | Mean measured values (calibration data set) and mean square error (RMSE), and d values in simulations of soil moisture in different depth of silt loam and clay soil

Soil profile depth	Silt loam ($cm^3\ cm^{-3}$)				Clay ($cm^3\ cm^{-3}$)			
(cm)	Mean	RMSE	d	Samples	Mean	RMSE	d	Samples
0–15	0.185	0.055	0.764	18	0.205	0.043	0.864	18
15–30	0.150	0.029	0.895	18	0.194	0.035	0.881	18
30–60	0.125	0.021	0.904	18	0.195	0.021	0.900	18
60–90	0.109	0.020	0.473	18	0.214	0.015	0.593	18

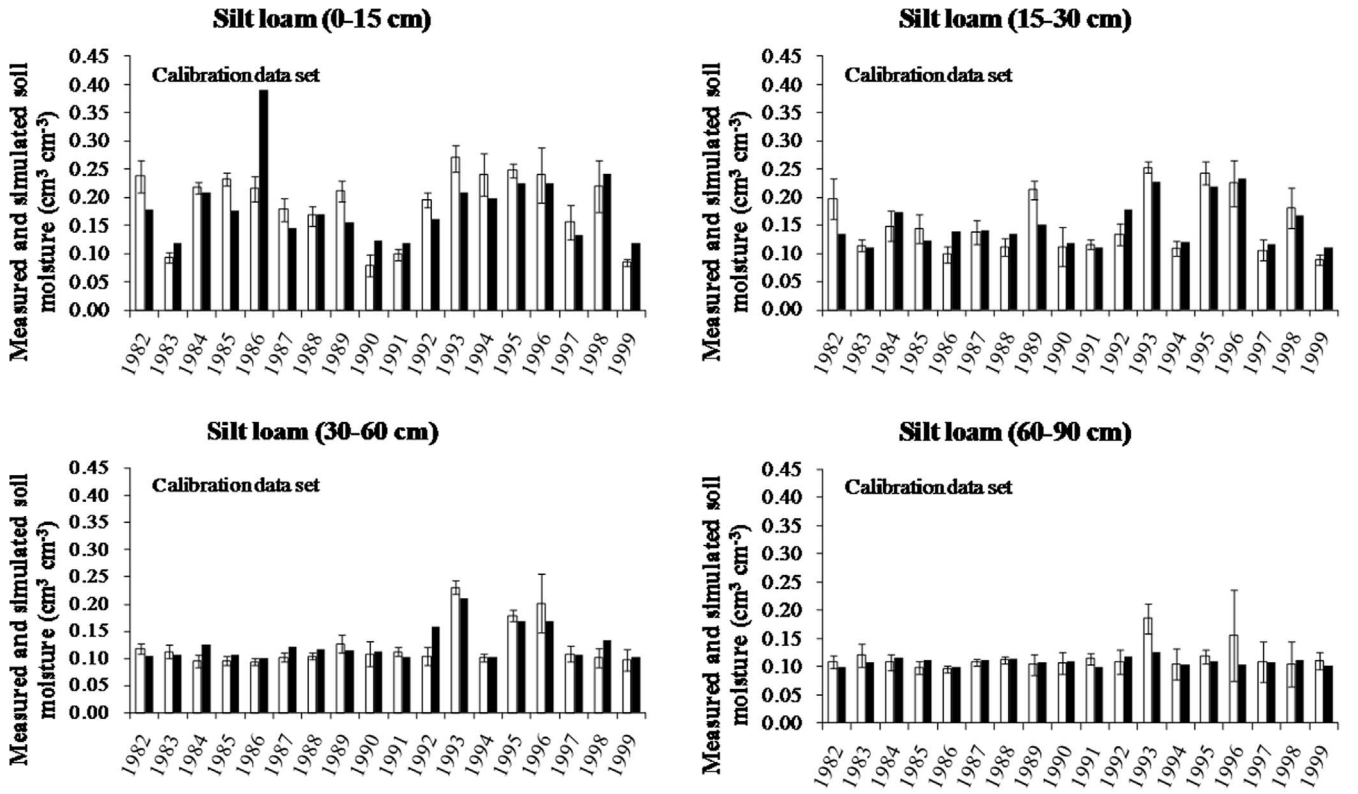


Figure 1 | Comparison of measured (open bars with error bars) soil moisture after harvest and corresponding simulated (solid bars without error bars) soil moisture in layers at silt loam soil site.

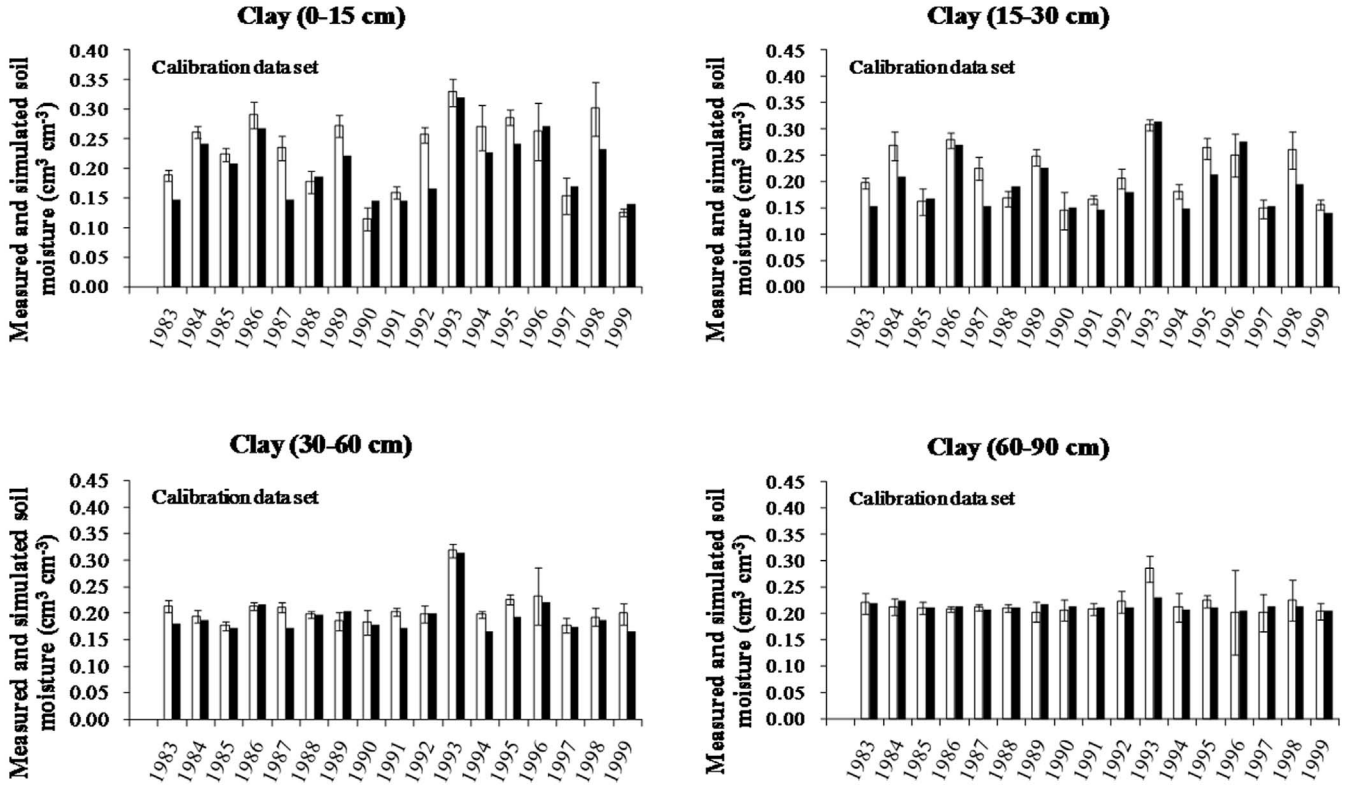


Figure 2 | Comparison of measured (open bars with error bars) soil moisture after harvest and corresponding simulated (solid bars without error bars) soil moisture in layers at clay soil site.

Table 5 | Calibration and validation of wheat phenology

	Year	RMSE	d	Samples
Calibration	2004	1.21	0.999	8
	2005	3.46	0.996	7
Validation	2006	3.152	0.997	6

phenology will affect accuracy of simulated final yield. These accumulated effects on final results of phenological development, WU, and crop yield are complex so it is infeasible to determine how the inaccuracies at each step accumulate to affect these final results. Instead, we determined the overall errors based on difference of each pairing of observed and simulated values. We evaluated the simulation results using: 1) RMSE (Eq.1); and 2) the index of agreement (d), which varies between 0 (poor model) and 1 (perfect model)[29] (Eq.2).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (1)$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(|P_i - O_{avg}| + |O_i - O_{avg}|\right)^2} \quad (2)$$

Where P_i is the ith simulated value, P_{avg} is the average of the simulated values, O_i is the ith measured value, O_{avg} is the average of the measured values, and n is the number of data pairs.

Results

Model calibration. From 1982 to 1999, wheat was grown in two soil textures. The grain yield and biomass collected in years 1983, 1986 and 1988 were missing, and thus excluded from the analysis. The two soil texture sites were simulated sequentially, with the simulation starting on 1 Jan. 1979 and ending on 31 Dec. 1999. Grain yield and biomass (at harvest) and soil moisture measurement (after harvest) were available for model calibration.

As shown in Table 4, soil moisture simulations in individual soil layers (0–60 cm) had RMSEs ranging from 0.020 to 0.055 ($cm^3\ cm^{-3}$) and from 0.015 to 0.043 ($cm^3\ cm^{-3}$) for the silt loam and clay sites, respectively. This indicates the soil moisture above 60 cm was well simulated. However, the soil moisture was not well simulated on both the silt loam and clay sites below 60 cm ($d < 0.593$). The variation in simulated soil moisture below 60 cm was smaller than those measured for both soil texture sites (Fig. 1 and 2). A plausible cause of the poor model performance is that the model assumed that half of the surplus water was held over to the next time step (i.e., the next month). This simple method of handling storage is not physically realistic and lowers the accuracy of the model simulations[28]. Thus, there is a need to improve model simulation of soil water in deeper soil layers. DSSAT simulates soil moisture more accurately during the growing season than before seeding or after harvest. This is not unexpected because DSSAT was primarily designed for simulating soil moisture-crop interactions[30]. The accuracy of soil moisture simulation is acceptable for estimating growing season WU.

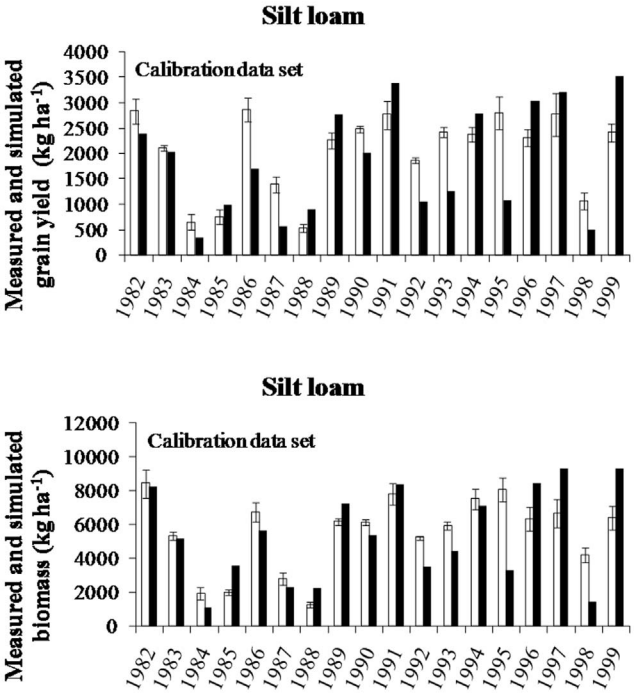


Figure 4 | Comparison of measured (open bars with error bars) and simulated (solid bars without error bars) grain yield and biomass ($kg\ ha^{-1}$) at silt loam soil site.

The wheat phenology in the CSM- CERES-Wheat model is controlled by growth stages, which are in turn driven by growing degree-days (GDD)[31]. The cultivar coefficients defined in DSSAT are specific to both the crop cultivar and the local climate, and must therefore be individually calibrated[12]. The two years of simulation RMSEs of wheat phenology was less than 3.46 (days) and d values were higher than 0.99 (Table 5 and Fig. 3), indicating that the DSSAT model simulated the wheat growth very well.

The simulated and measured grain yields for silt loam and clay from 1982 to 1999 are displayed in Fig. 4 and 5. The annual fluctuation of grain yield and biomass were reasonably simulated for both soil texture sites. With the exception of the grain yield and biomass in 1995 in silt loam soil, all of the grain yield and biomass were simulated well with RMSEs of 777 ($kg\ ha^{-1}$), and d value of 0.808 for grain yield and an RMSE of 1871 ($kg\ ha^{-1}$), and d value of 0.836 for biomass (Table 6). The grain yield and biomass was also well simulated in clay soil with the exception of grain yield in 1993 and biomass in 1982. The deviations between simulated and mea-

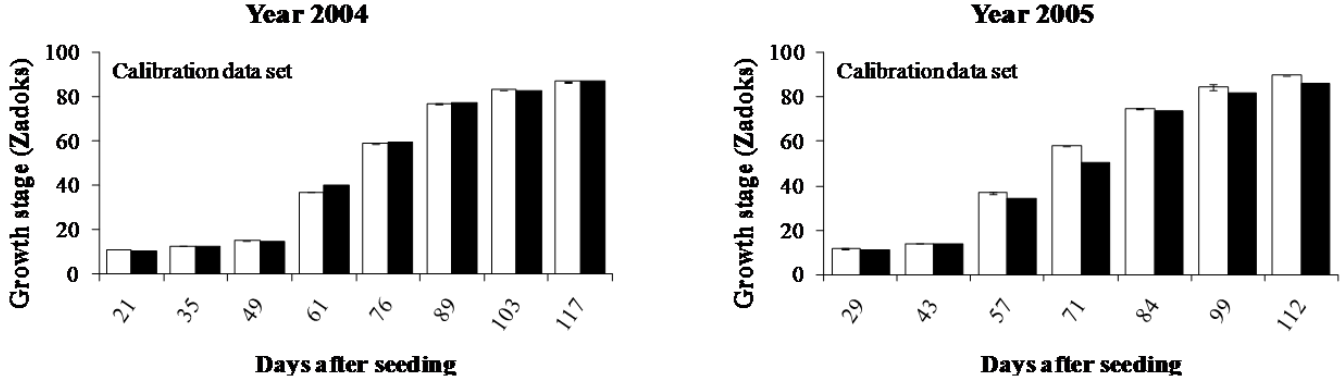


Figure 3 | Comparison of measured (open bars with error bars) and simulated (solid bars without error bars) wheat phenology.

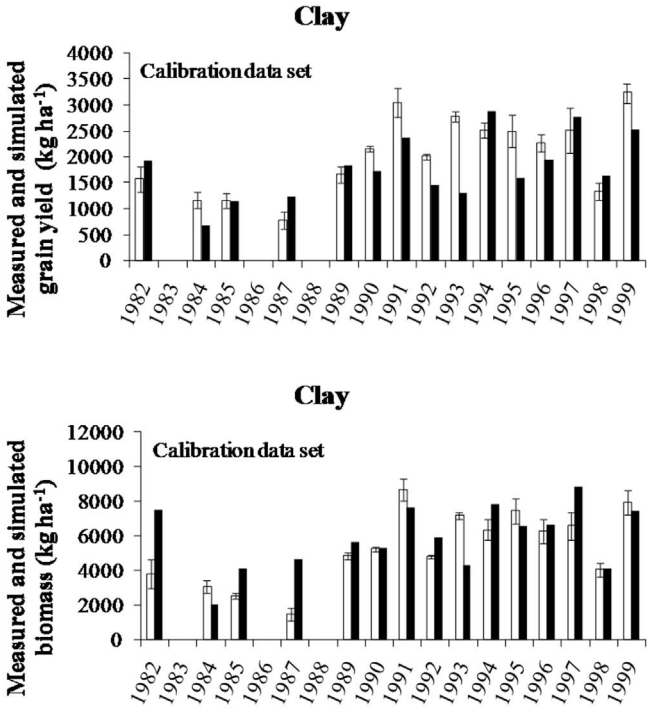


Figure 5 | Comparison of measured (open bars with error bars) and simulated (solid bars without error bars) grain yield and biomass (kg ha^{-1}) at clay soil site.

sured grain yield and biomass in these individual years were not good for either soil texture sites, but the overall accuracy were on the same order as those obtained by others[32,33]. The large differences between simulated and measured grain yield and biomass may be related to our assumptions regarding soil physical properties and cultivar characteristics. The imprecise simulation of grain yield and biomass in these individual years probably reflects factors and/or events that are not considered in the model, such as heavy rainfalls, high winds, weed competition, crop diseases, hail damage, etc[12].

Inspection of the data comparisons presented in Fig. 1 to 5 indicates that the model was adequately calibrated for soil moisture, wheat phenology, grain yield and biomass.

Model validation. The results from the calibrated model were then compared with the remaining data, which were a continuation of the long-term study and the physiological study. The soil moisture simulations, in terms of RMSE in various soil layers of the silt loam and clay sites, ranged from 0.025 to 0.046 (cm^3 cm^{-3}), and from 0.031 to 0.042 (cm^3 cm^{-3}), respectively (Table 7). Their corresponding d values were higher than 0.9 in all layers. Figure 6 and 7 shows that the simulated soil moisture in all layers are scattered more or less equally around the 1 : 1 line for all textures, indicating that there were no systematic deviations in the model simulation, and that the soil moisture was simulated reasonably well for both soil textures.

Wheat phenology was fairly well simulated with both a low RMSE (3.15 days) and a high d value (0.997) in year 2006 (Table 5 and Fig. 8). Overall, the simulated mean and ranges of grain yields for the two soil texture sites corresponded closely to observed means and ranges (Fig. 9 and 10). The model also correctly simulated the biomass of the two soil texture sites with a relative low RMSE (<1688 kg ha^{-1}) and a high d value (>0.77) (Table 8), and equally distributed scattering around the 1 : 1 line for both soil textures (Fig. 9 and 10).

Comparison of water use between silt loam and clay soil. After validation, the model was then used to compare the precipitation use (PU) and water use (WU) between the two soil textures based on the simulation outputs (soil moisture in profile, maturity, grain yield). The PU was defined as total precipitation received between seeding and maturity for each growing season. The WU was calculated as the difference of soil moisture (0 to 1.8 m depth) between seeding and maturity, plus PU[34]. As shown in Fig. 11, the WU for the two soil textures has a similar trend over the years due to the predominant common effect factor of precipitation amount during the growth period.

The difference in WU between the two soil textures are mainly affected by soil differences in water holding capacity. These differences ranged from 2 to 57 mm. A minor amount of the differences in WU would be due to the 1 to 7 day differences between the seeding dates at the two sites. A noticeable trend was found that the clay soil has higher WU than silt loam soil in most drought years (defined as those years, 1984, 1985, 1987, 2001, 2007 and 2009, that fell into the lowest quantile of growing season precipitation). This result explains why the clay soil out-yields the silt loam soil in most drought years (Table 1).

The relationship between grain yield and the WU was linear for both silt loam and clay soils (Fig. 12). The slopes for the two equa-

Table 6 | Mean measured values (calibration data set) and mean square error (RMSE), and d values in simulations of grain yield and biomass of silt loam and clay soil

	Grain yield (kg ha^{-1})				Biomass (kg ha^{-1})			
	Mean	RMSE	d	Samples	Mean	RMSE	d	Samples
Silt loam	2042	777	0.808	18	5512	1871	0.836	18
Clay	2049	599	0.791	15	5353	1785	0.766	15

Table 7 | Mean measured values (validation data set) and mean square error (RMSE), and d values in simulations of soil moisture in different depth of silt loam and clay soil

Soil profile depth	Silt loam (cm^3 cm^{-3})				Clay (cm^3 cm^{-3})			
(cm)	Mean	RMSE	d	Samples	Mean	RMSE	d	Samples
0–15	0.181	0.027	0.983	12	0.223	0.042	0.996	12
15–30	0.162	0.046	0.965	12	0.211	0.032	0.999	12
30–60	0.131	0.037	0.980	12	0.209	0.036	0.999	12
60–90	0.111	0.025	0.990	12	0.219	0.031	0.995	12

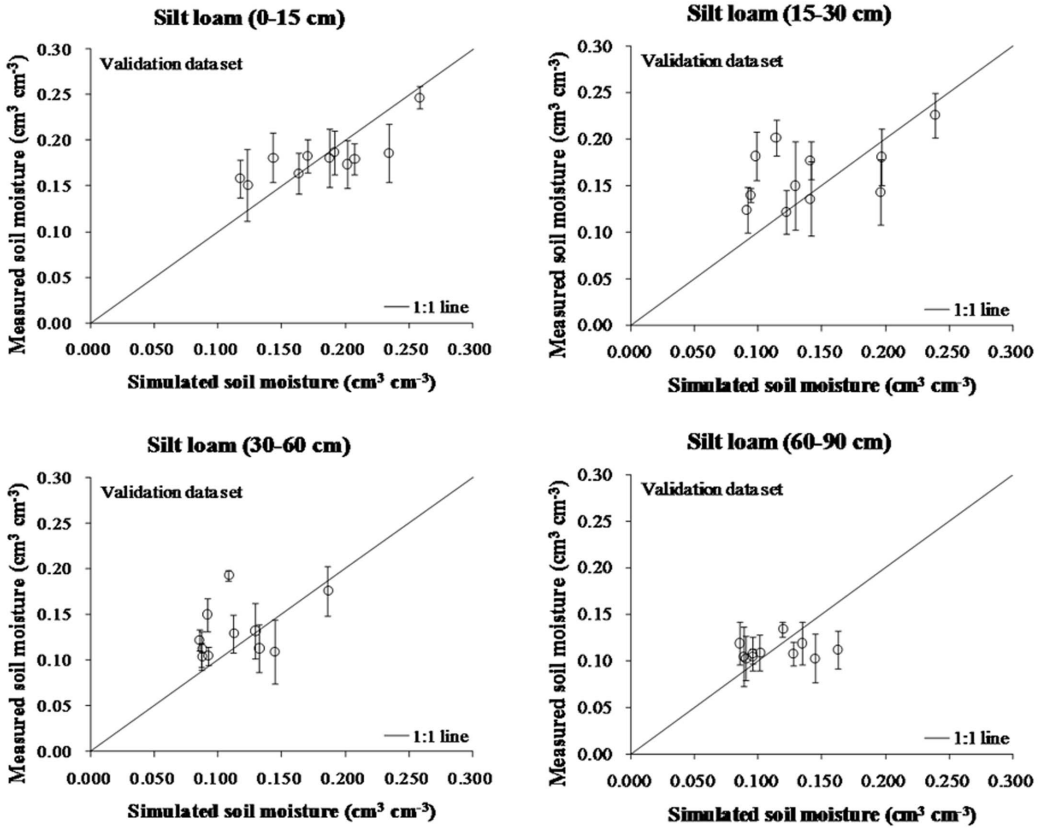


Figure 6 | Comparison of measured (validation data set) vs. simulated soil moisture in layers at silt loam soil site. Error bars indicate standard deviation of measured means.

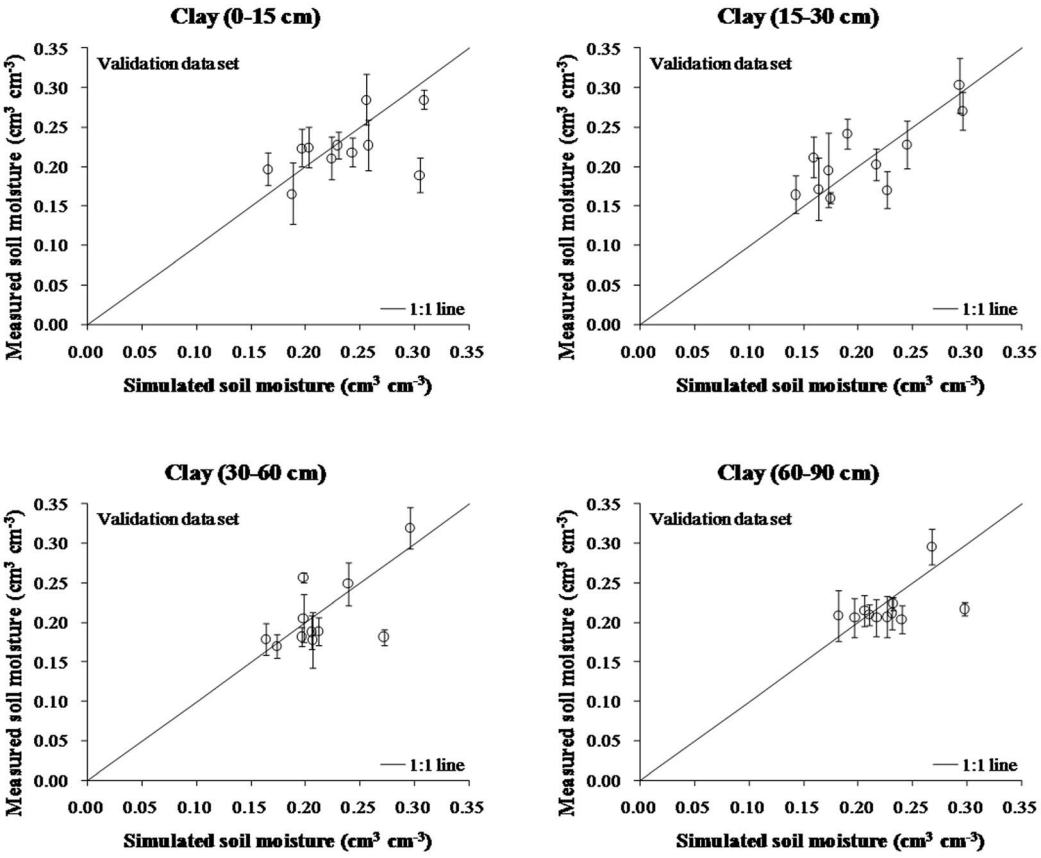


Figure 7 | Comparison of measured (validation data set) vs. simulated soil moisture in layers at clay soil site. Error bars indicate standard deviation of measured means.

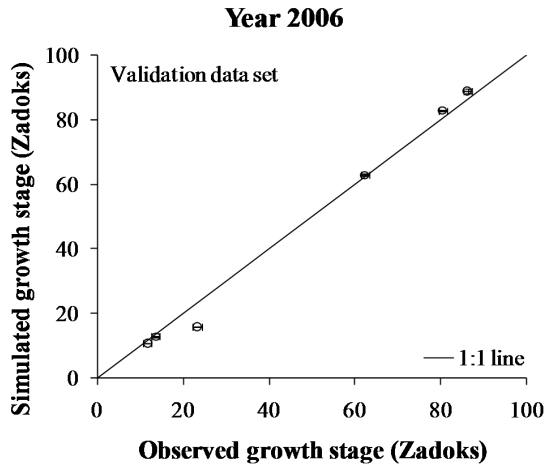
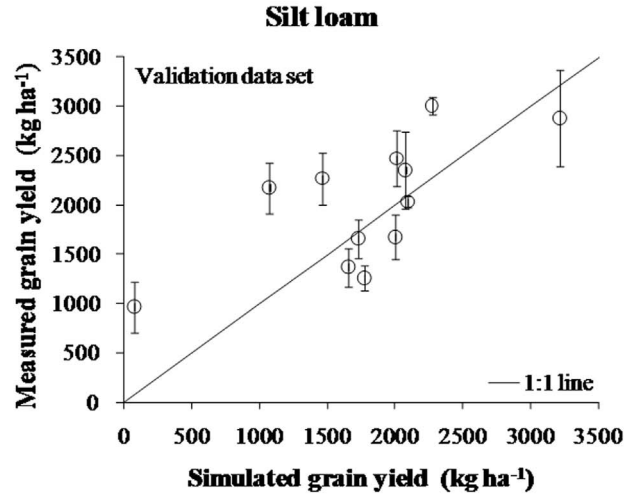


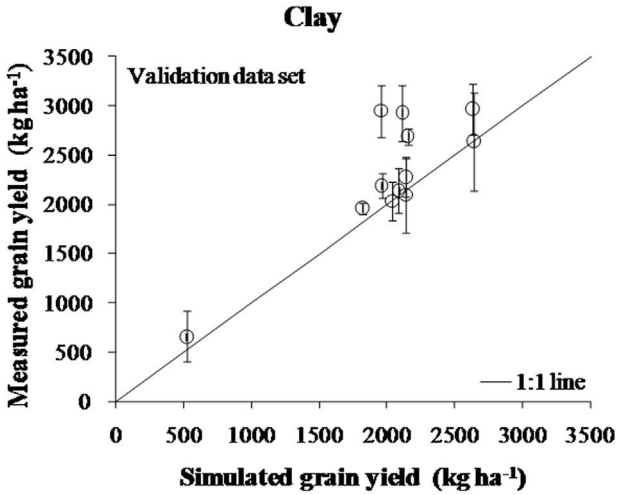
Figure 8 | Comparison of measured (validation data set) vs. simulated wheat phenology in year 2006. Error bars indicate standard deviation of measured means.

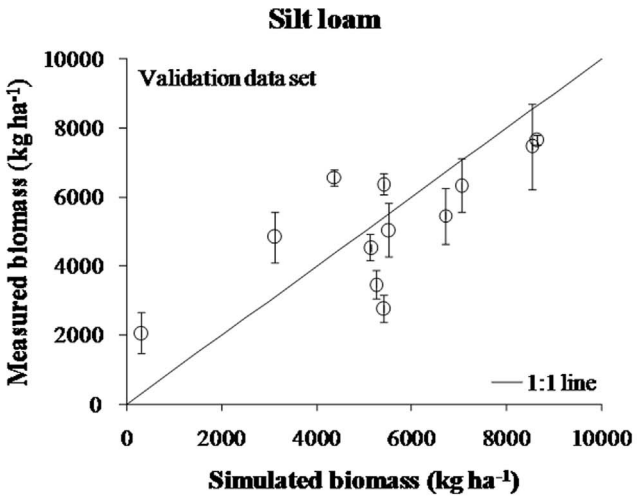
tions are 8.245 and 5.962, respectively, and are assumed to provide some measure of sensitivity of grain yield to WU. The larger slope for wheat grown on a silt loam soil shows it is more sensitive to WU than wheat grown on a clay soil. The R^2 of fitted equations of simulated WU and simulated yield of silt loam was higher than that of clay soil, also indicating that silt loam is more sensitive than clay soil, which coincides with our previous statistical analysis[15]. The R^2 of fitted linear relationships between simulated WU and simulated yield were much higher than those between PU and simulated yield for both silt loam and clay soils. This demonstrates that, yield variation is much better be explained by WU than by PU. This result clearly shows that soil texture plays an important role in affecting the soil × crop interaction and thus the yield.

Discussion

The objective of this study is to evaluate the effect of soil texture on wheat productivity in rain-fed condition. However, to understand the variation led by soil texture is challenging due to a lot of confounding factors. To achieve the goal of our objective, we adopted an agricultural system model (CSM-CERES-Wheat model). It is largely recognized that the model need to be well calibrated and validated before applied for account for the impacts[35,36]. Therefore, a long-term (1982–2011) continuous wheat experiment in southwest







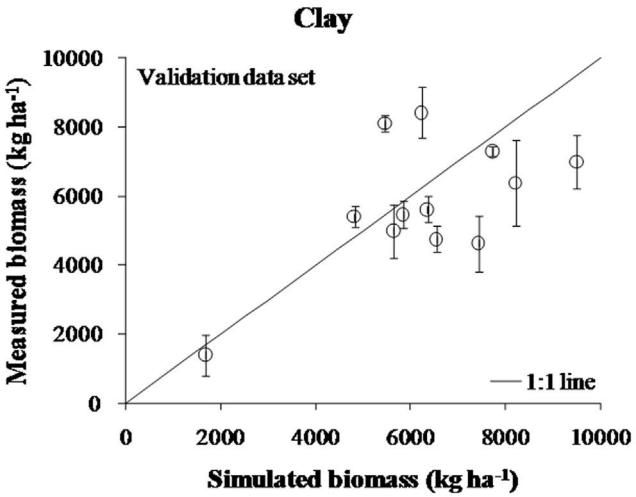


Figure 9 | Comparison of measured (validation data set) vs. simulated grain yield and biomass at silt loam soil site. Error bars indicate standard deviation of measured means.

Figure 10 | Comparison of measured (validation data set) vs. simulated grain yield and biomass at clay soil site. Error bars indicate standard deviation of measured means.

Table 8 | Mean measured values (validation data set) and mean square error (RMSE), and d values in simulations of grain yield and biomass of silt loam and clay soil

	Grain yield (kg ha^{-1})				Biomass (kg ha^{-1})			
	Mean	RMSE	d	Samples	Mean	RMSE	d	Samples
Silt loam	2012	581	0.792	12	5225	1494	0.839	12
Clay	2296	426	0.868	12	5795	1688	0.770	12

Saskatchewan, on both silt loam and clay soils was used to calibrate and validate the model. This data set is ideal for investigation of soil textures' impact, which because other factors such as cultivar characteristics and field management are all same in these two sites every year. The two sites also have very similar weather condition since only 30 km away from each other. Therefore, the main contribution to yield difference should due to soil texture.

The model performance for simulating yields, although not better than for soil moisture and phenology, was comparable to that of other research with simulation models[31,32]. The large differences between simulated and measured grain yield and biomass for some individual years may be related to inaccuracies in our assumptions regarding soil physical properties and sampling procedures. For example, grain yield simulation in 1993 at clay soil site deviated from the measured by 2819 kg ha^{-1} (error of −39%). During this crop season, the model was not able to simulate the soil water and nitrite dynamics well, leading to a water stress (0.27) during tillering stage and high nitrite stress (0.64) during the grain filling stage resulting in under prediction of biomass and grain yield (data not shown). Simulated biomass was higher than measurement in 1982 at clay soil site. This is partially due to sampling occurring at full maturity, which was about 10–20 days after physiological maturity when the wheat reached its maximum biomass. Some senescent leaves, ripened spikes and broken tillers fall to the ground during this period, and are difficult to recover. The inaccurate simulation of grain yield (1993) and biomass (1982) may also reflect factors and/or events that are not considered in the model, such as heavy rainfalls, high winds, and hail damage, etc., which need to be improved with further study.

The simulation output of validated model was used to analyze the WU difference caused by soil texture. The simulated result showed that clay soil has higher WU than silt loam soil in most dry years, which agrees with research conducted in the same area as our study, by Lehane and Staple (1953)[37]. They also found that in a dry year, wheat grown on clay soil had a higher yield than those grown on silt loam soil. They attributed this effect to differences in crop access to the available moisture between soil textures. Wheat grown on coarser soil textures are able to readily extract stored soil water and spring precipitation, leading to lush early growth and heavy tillering. Providing there is sufficient summer rains to replenish soil water,

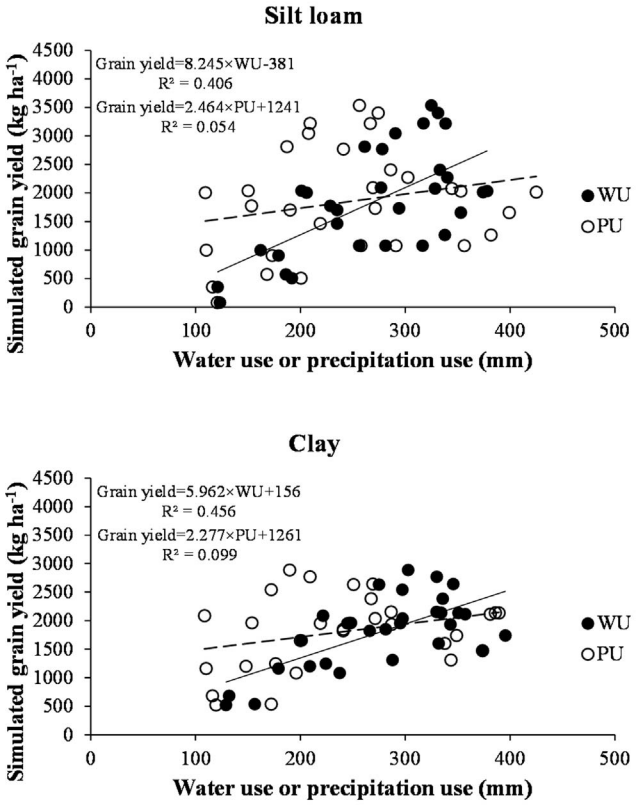


Figure 12 | Liner relationships between water use (WU) or precipitation use (PU) and simulated grain yield in silt loam and clay soil over 30 years (1982–2011).

these crops have good growth and high yields. However, if soil water is not well replenished by summer rains, the wheat grown on coarser textured soils is unable to extract sufficient soil water to overcome water stress and so productivity suffers. In contrast, the wheat grown on fine textured soils are less able to extract soil moisture in the spring due to the water holding characteristics of the clay soil. Productivity is thus limited. However, if subsequent summer rains are insufficient to replenish soils water, the crops grown on clay soil are still able to access remaining soil water that they did not use in the spring. The results is that crops grown on clay soils are less sensitive to water use than those grown on coarser textured soils and produce higher yield in drought years[38]. Our simulation result concurs with these reports.

In conclusion, we found the CSM-CERES-Wheat model can be used as a tool to estimate the soil texture effects on crop productivity and WU. Crops grown on clay soil has better drought tolerance than those grown on silt loam in the climatic conditions of our study. We

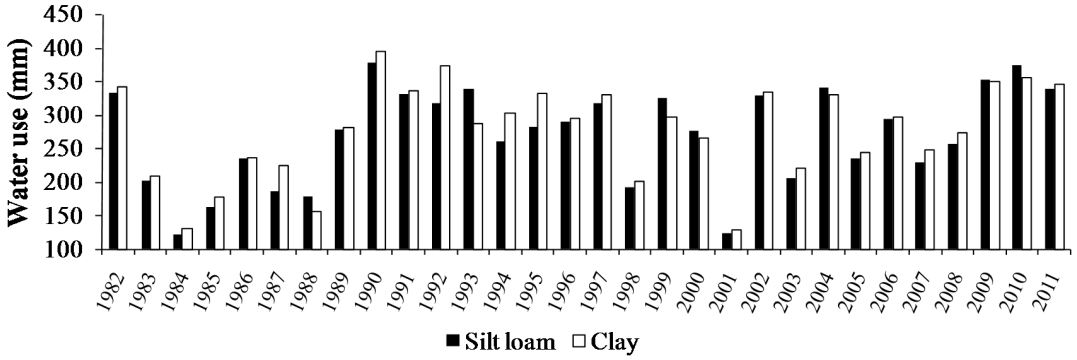


Figure 11 | Comparison of simulated water use in silt loam and clay soil.

suggest that this work on estimating soil texture effects on WU and yield with simulation models be validated over a wider range of soil textures. The use of simulation models may lead to a better understanding of the crop–soil texture interactions, enabling crop breeders to analyze the performance of different crop genetics with regard to the broad soil textures that they target. For example, for cultivars targeted for production on clay soils, developing a variety that can extract more water from clay soil may improve both drought tolerance and production.

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Author contributions

Y.H. and H.W. analyzed data; H.W. and B.M. performed research; Y.H., K.H., L.H. and H.W. wrote the paper.

Additional information

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