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RESEARCH

Simulating Crop Productivity in a Triple Rotation in the Semi-arid Area of the Aral Sea Basin

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Abstract

Farmers face increased risks and vulnerability to the effects of climate change and land degradation on crop production due to the lack of information and impact assessment. This is especially true in the Khorezm, an irrigated agricultural region near the Aral Sea Basin (Uzbekistan) which represents eight million of irrigated land in Central Asia. Water scarcity requires research and introduction of alternative crops into a common winter wheat–cotton rotation. Mung bean (*Vigna radiata*) is considered as a drought-tolerant crop that could be implemented in Khorezm and other similar drought prone areas. The main objective of this study was modeling the triple rotation sequenced the winter wheat (WW), summer mung bean (MB) and cotton (C) as a single cropping system. Specific objectives were to (1) update the parameterization of the irrigated winter wheat and cotton modules in CropSyst to identify the key variables impacting the triple rotation (WW–MB–C) on overall crop yield; (2) to parameterize and validate the developed (CropSyst-based) model using controlled triple rotation data and (3) carry out scenario analyses to capture the influence of soil fertility levels and irrigation water shortage on crops growth, development and yields. The results revealed, for the first time, the impact of different soil-ecological factors such as high soil fertility (HSF) and low soil fertility (LSF) varying levels of irrigation water availability on crops in the triple crop rotation. Compared to LSF simulated yields of winter wheat and cotton under HSF were increased with 0.58 Mg ha^{-1} for WW grain and 0.21 Mg ha^{-1} for cotton while mung bean grain yields were not affected by different soil fertility levels. Scenario analyses showed the possibility of reduced (by 20%) irrigation for triple crop without the effect on yield. However, compared to full irrigation scenario, reduction of irrigation for 40 and 60% could decrease the rotation crops yields up to 33% and 40%, respectively. The developed model could be useful to increase the understanding of the nexus of food, energy and water in Khorezm and comparable regions of Central Asia, and to inform decision-making about sustainable use of available water resources.

Keywords CropSyst · Water scarcity · Wheat–mungbean–cotton rotation · Climate change

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Introduction

There are emerging challenges faced by farmers that increase their risks and vulnerability to the effects of climate change and land degradation due to the lack of information and assessment of the climate change impact on crop production. An archive of studies worldwide underlines that crop rotation is a well-recognized practice to counterbalance a series of challenges such as soil health and fertility decline, soil degradation and erosion (Wright et al. 2005), but also is an effective means for pest, disease and weed control. The impact of crop rotation is mirrored in a reduction of production risks, more stable crop yields and returns to farmers without compromising the environment (Cook and Ellis 1987). Various modeling approaches are extensively used for assessment of the impact of climate change on crop growth and exploring different scenarios for crop management.

Despite the recurrently recognized and obvious benefits, crop rotations are not always and everywhere respected, albeit for a scope of reasons, which is exemplified in the case of cotton production (*Gossypium hirsutum* L.). For example, a cotton–wheat rotation followed by soybean or cotton-double-cropped soybean was effective in the southeastern region of USA due to an increase in soil organic matter (SOM) that increased in turn cotton yields (Burmester et al. 2002). In Australia cotton growers used either a 1:1 or 2:1 cotton–wheat rotation (Cooper 1999) because soil structure, N-cycling, and lint yield and fiber quality of cotton increased when replacing continuous cotton or cotton rotated with sorghum or soybean with wheat (Constable et al. 1992). This was attributed to improved conservation of soil moisture as cotton–wheat rotations included a ~ 10 month fallow between wheat harvest and cotton planting. Instead, the previous practices of continuous cotton, cotton–soybean or cotton–sorghum rotations included much shorter fallow periods in winter (Hulugalle and Scott 2008). Also, cotton-wheat rotations are widely practiced by cotton growers in China (Zhonghu and Alain Bonjean 2010) and Pakistan (Abid et al. 2015).

The pre-Soviet crop cultivation practices in Central Asia implemented key principles of crop rotation (Cook and Ellis 1987) as they included the cultivation of legumes (e.g. alfalfa), grain crops (e.g. wheat, sorghum, maize), melons and gourds (pumpkin) in rotation with cotton sequences of a maximum of 2 years. But during unprecedented intensification of cotton production in 20th century, a practice of cotton monoculture was introduced in the five Central Asian countries (Mandelbaum 1994), which has recurrently been identified as one of the culprits of widespread soil fertility decline owing to land degradation, the ill-management of irrigation water and high inputs of chemicals (Conrad et al. 2016; Akramkhanov et al. 2012).

After independence in 1991, Uzbekistan, decreased its area under cotton by introducing winter wheat (WW) (Kienzler et al. 2011). But farmers gradually included the use of a third crop in the crop portfolio, albeit still dominated by wheat and cotton, and developing slowly a "double-season" system. By including typical crops such as maize and vegetables, but also leguminous crops such as mungbean, cowpea, and soybean, a more diverse, agro-biodiversity is unfolding.

Additional research is urgently needed to update the knowledge and understanding of effects of management practices within cotton rotations and adapt these to the present developments. Yet, to conduct multi-location, multi-factorial field experiments with numerous crops and over many years, the necessary funds and resources are usually limited. Crop simulation models, therefore, can help to decrease this hurdle and to cope with limited data access while still considering the crop–soil–environment interactions.

Earlier crop modeling efforts in the region (e.g. Djumaniyazova et al. 2010; Sommer et al. 2008) have addressed the parameterization and validation of the CropSyst dynamic model for irrigated wheat and cotton. Yet, they did not capture the more recent development of "double-season" cropping and farmer innovative crop rotations such as reflected in the WW–summer mungbean–cotton rotation under the irrigated agro-ecological conditions in Uzbekistan. The objectives of this study, therefore, were to (i) update the parameterization of the irrigated WW and cotton modules in CropSyst, (ii) parameterize and validate the WW–mungbean–cotton rotation module in CropSyst for the irrigated floodplain conditions in northwest Uzbekistan and (iii) carry out scenario analyses to capture the influence of soil fertility levels and irrigation water shortage on crops growth, development and yields.

Materials and Methods

Study Region

The Khorezm region with its irrigated area of about 0.27 Mha represents well the irrigated agro-ecosystems of Uzbekistan.

The Khorezm region is located in northwest Uzbekistan at 60.05°–61.39° N latitude and 41.13°–42.02° E longitude. Elevation ranges 90–138 m above sea level. The climate in the study area is strongly continental and arid with annual mean precipitation of 100 mm, which falls mainly outside the summer growing season, crop production is possible with irrigation only. The annual mean air temperature is 13 °C; but maximum of above 45 °C (July 2011) and minimum of about − 25 °C (January 2008) were recorded during the study period 2008–2011. Nightfrost and cold spells can occur from October onwards. Spring is short, but summers are long, hot and dry. The climatic conditions favor growing of annual crops such as cotton, legumes, maize, winter wheat, and vegetables.

The study region is characterized by shallow groundwater table often in the range of 1.5 m with moderate salinity levels of 1.75 g l^{-1} (Ibrakhimov et al. 2007, 2011). The database of Khorezm soils indicate that the median of topsoil salinity EC_e reach 10 dS m^{-1} before leaching, and decrease significantly by half in the lower horizons (Akramkhanov et al. 2012). The typical salinity type of these soils is chloride-sulphate (Akramkhanov 2005).

Field Experiment and Data Collection

For a parameterization and validation of the CropSyst model under the irrigated agro-ecological conditions of this region, data were drawn from previous studies (ZEF/UNESCO Project in 2008–2011 at the Khorezm Experiment Station of the Cotton Breeding, Seed Production and Agro-Technologies Institute, Uzbekistan) (Babadjanova et al. 2012; Devkota et al. 2013; Haitbayeva 2019).

The soil under the 4-year field experiment was a Calcic Gleysol (Table 1) with shallow (150–200 cm) and saline groundwater and slightly (Electrical conductivity 2.3–4.0 dS/m) saline. Triple crop rotation with the crop sequence "WW–summer mungbean–cotton" was subjected to a series of intensive study steps (Table 2).

An effort was made to set-up a series of consecutive experiments for collecting data typically for model parameterization and other purposes. Therefore, all necessary biophysical data were collected from a crop rotation cycle during 2008–2010 (Fig. 1, Table 2). Model validation was effective by collecting data while considering differences in time and space. Therefore field data for the model validation were collected from another crop rotation cycle conducted from 2009 to 2011 (Table 2). Experimental plots sized 7.2 by 15 m in the blocks were replicated four times.

The parameterized and validated CropSyst model was used next for simulating the influence of different soil textures and soil organic matter (SOM) levels on crop growth and yields in the WW–summer mungbean–cotton cropping system. Soil with high SOM was considered as composite indicator of rich soils in the region with accompanying factual rates of nutrients. There was no intention and possibility to discern effect of different components of rich soil on crop yields in the model. The data was collected from several fields: (a) a reference field (Field #1) was a silty-clay (top 0–30 cm soil layer) in texture with lower concentrations of SOM (Table 2) and (b) Field #2 was loamy in texture with high SOM (Table 1). Both, Field #1, hereafter low soil fertility (LSF) and Field #2, high soil fertility (HSF), were located in Urgench district of the Khorezm region. During simulation runs the recommended rates of chemical fertilizers had been applied: e.g. $N_{180}P_{130}K_{100}$ kg ha^{-1} for winter wheat, $N_{30}P_{120}K_{100}$ kg ha^{-1} for mungbean and $N_{200}P_{140}K_{100}$ kg ha^{-1} for cotton are actual application rates.

Plant and Soil Sampling

Soil sampling, chemical analyses, the estimation of leaf area index (LAI) and aboveground biomass (AGB) and other yield parameters, as well as other biophysical data collected during WW and cotton cultivation, have been reported previously (Djumaniyazova et al. 2010; Sommer et al. 2008). Plant samples in the mungbean field were taken from a 0.83 m sampling row at S10, S13, S65, S75, S79, and S89 growth stages (BBCH Monograph 2001). The samples were separated into stems, leaves, and pods. The dry matter (DM) of the AGB was determined after drying subsamples with a known fresh weight at 70 °C for 72 h in a

Table 1 Soil physical and chemical characteristics of the Calcic Gleysol in the Khorezm region used during the simulation analyses

	Field 1 (LSF)				Field 2 (HSF)			
Depth (cm)	0–30	30–50	50–70	70–100	0–30	30–50	50–70	70–100
Sand (%)	36	19	21	23	52	50	45	40
Silt (%)	54	67	67	58	35	36	38	43
Clay (%)	10	14	12	19	13	14	17	17
Soil texture	Silty clay	Silty clay loam	Silty clay loam	Silty clay	Loam	Loam	Loam	Loam
Bulk density (g cm^{-3})	1.36	1.42	1.40	1.41	1.64	1.53	1.57	1.56
SOM (g kg^{-1})	4.2	3.2	2.7	1.7	6.3	5.3	4.3	3.1
Total N (g kg^{-1})	0.5	0.4	0.2	0.2	0.5	0.4	0.3	0.2
NO_3-N (mg kg^{-1})					8.5	5.4	4.0	5.4
Available P (mg kg^{-1})	29	16	9	8	18	13	13	10
Exchangeable K (mg kg^{-1})	120	100	90	90	227	205	199	199

LSF low soil fertility, *HSF* high soil fertility

Table 2 Characteristics of field experiments for model parameterization and validation in 2008–2011 years

	Model parameterization (2008–2010)	Model Validation (2009–2011)
Winter wheat (*Triticum aestivum* L.)	Crop: cv. Krasnodarskaya-99 broadcast planted Seeding rate: 200 kg ha^{-1} on 17 September 2008 and harvested on 20 June 2009 Fertilization: $N_{240}P_{130}K_{90}$ kg ha^{-1} of mineral fertilizer applied as urea, single superphosphate, and potassium chlorine Irrigation: 464 mm of irrigation water during 7 events Above ground biomass 12615 kg ha^{-1} Grain yield 5969 kg ha^{-1}	Idem Seeding rate: 200 kg ha^{-1} on 18 September 2009 and harvested on 22 June 2010 Fertilization: Idem Irrigation: 495 mm of irrigation water during 7 events Above ground biomass 10778 kg ha^{-1} Grain yield 5119 kg ha^{-1}
Mungbean (*Vigna radiate* [L.] Wilcz.)	Crop: Radost with an inter-row distance of 0.6 m. Seeding rate: 18 kg ha^{-1} on 03 July 2009 and harvested on 26 September 2009 Fertilization: $N_{30}P_{120}K_{100}$ kg ha^{-1} of mineral fertilizer applied as urea, single superphosphate, and potassium chlorine Irrigation: 200 mm of irrigation water during 4 events Above ground biomass 4220 kg ha^{-1} Grain yield 1330 kg ha^{-1}	Idem Seeding rate: 18 kg ha^{-1} on 05 July 2010 and harvested on 29 September 2010 Fertilization: idem Irrigation: 200 mm of irrigation water during 4 events Above ground biomass 3286 kg ha^{-1} Grain yield 1240 kg ha^{-1}
Cotton (*Gossypium hirsutum* L.)	Crop cv. Khorezm-127 with an inter-row distance of 0.9 m Seeding rate: 60 kg ha^{-1} on 23 April 2010 and harvested in Sept–Oct. 2010 Fertilization: $N_{240}P_{140}K_{100}$ kg ha^{-1} of mineral fertilizer applied as urea, single superphosphate, and potassium chlorine Irrigation: 497 mm of irrigation water during 6 events Above ground biomass 10701 kg ha^{-1} Cotton seed-lint yield 3163 kg ha^{-1}	Idem Idem Fertilization: idem Irrigation: 420 mm of irrigation water during 5 events Above ground biomass 10744 kg ha^{-1} Cotton seed-lint yield 3330 kg ha^{-1}

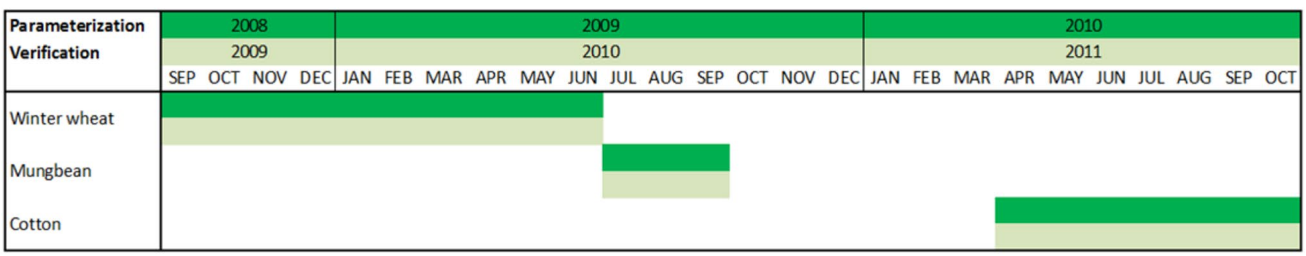


Fig. 1 Timeline of vegetation duration of the three crops in the treble "winter wheat–mungbean–cotton" rotation during model parameterization and evaluation

forced air convection oven. Leaf area (LA) was measured with the LI-COR 3100 leaf area scanner, and the LAI was next calculated as total LA over the total ground area. Corresponding leaf DM was determined after oven-drying, and subsequently, the Specific Leaf Area (SLA, m^2 kg^{-1}) was calculated. At harvest, plants were sampled from 1.67 m of each two central rows for determining AGB, yield and harvest index (HI).

Crop Model and Scenarios

Used for simulations was the CropSyst model (Stockle et al. 2003), version 4.19.06. Simulated was the impact of different soil-ecological factors on crops in the treble crop rotation "WW–summer mungbean–cotton" in the irrigated agro-ecological condition in the Khorezm region (Table 3). Important for the choice of the model was its ability to simulate productivity of crops in rotation. The dynamic CropSyst model is capable also of considering the impact of shallow and saline groundwater and soil salinity on crop growth, both typical for the study region .

Since the fields in Khorezm, suffer from soil salinity and/or shallow (saline) groundwater, CropSyst's soil salinity and shallow groundwater routine were enabled. Shallow groundwater dynamics were entered in the model as observed on-site.

The fits between the simulated and empirical values for the various parameters examined in the treble crop rotation "WW–summer mungbean–cotton" provided the necessary confidence for using CropSyst in a number of scenarios. Scenario analysis has been conducted in the same experimental region with the same soil, plant and weather parameters.

Table 3 CropSyst model settings for crops in the treble rotation "winter wheat–summer mungbean–cotton"; model was parameterized using observed (O), calibrated (C) and default (D) data

	Winter Wheat	Mungbean	Cotton	Source
Life cycle and land use	Annual row crop			
Photosynthetic pathway	C3	C3	C3	
Harvested biomass	Seed	Seed	Seed§	
Biomass/transpiration coefficient (kg m^{-2} kPa m^{-1})	5.1	5.0	5.0	C
Radiation use efficiency (g MJ^{-1})	3.0	2.5	2.5	C
Evapotranspiration crop coefficient at fully canopy	1.0	1.1	1.1	C
Optimum mean daily temperature for growth	10	25	25	C
Initial green leaf area index (m^2 m^{-2})	0.011	0.011	0.011	D
Expected maximum LAI	5.0	3.5	3.0	O
Specific leaf area, SLA (m^2 kg^{-1})	15.0	23.0	13.5	O
Leaf/stem partition coefficient, SLP	2.0	3.0	3.0	C
Leaf area duration (°C day)	740	1000	950	C
The extinction coefficient for solar radiation	0.7	0.9	0.9	C
Accumulated growing degree days from:				
Seeding to emergence (°C day)	95	45	170	O
Seeding to peak LAI (°C day)	440	940	1200	O
Seeding to flowering (°C day)	510	900	1165	O
Seeding to beginning grain filling (°C day)	590	1020	1180	C
Seeding to maturity (°C day)	1040	1400	1510	O
Base temperature (°C)	3	3	8	C
Cutoff temperature (°C)	25	22	20	C
Unstressed harvest index	0.41	0.40	0.35	O

§Assumed to include cotton lint

The simulation of the impact of water availability included the assumption of four levels (application of irrigation for WW–Mb–Cot Baseline 464–200–497 mm; Medium 278–120–298; High water stress 185–80–198; Very high water stress 92–0–99 mm respectively) of irrigation water availability. And, in response to these, four groundwater table shallow (1–2 m), medium (1.8–2.5 m), deep (> 3.00) and below 3 m scenarios (Table 4). Used the fertilizer rates are actual for the high (WW $N_{180}P_{130}K_{100}$ kg ha^{-1}, Mb $N_{30}P_{120}K_{100}$ kg ha^{-1}, Cot $N_{200}P_{140}K_{100}$ kg ha^{-1}) and low (WW $N_{100}P_{130}K_{100}$ kg ha^{-1}, Mb $N_0P_{120}K_{100}$ kg ha^{-1}, Cot $N_{125}P_{140}K_{100}$ kg ha^{-1}) scenario. It was assumed furthermore that in water-scarce years the amount of irrigation water applied would be less and each scenario with different access to irrigation water will last for 2 years, i.e. the entire cycle of the treble crop rotation.

Statistical evaluations of results comprised the calculation of the root mean square error has a minimum and optimum value at 0. It is a difference-based measure of the model performance in a quadratic form, and it is fairly sensitive to outliers:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Observed_i - Simulated_i\right)^2}{n}}$$

and

$$RRMSE = \frac{RMSE}{Average(observed)} \cdot 100$$

RMSE is one of the most widely used statistical indicators in environmental estimation models (Jacovides and Kontoyiannis 1995). It represents a measure of deviation between observed and simulated values, small RMSE values indicate good performance (Loague and Green 1991). The simulation is considered excellent with RRMSE < 10%, good if 10–20%, fair if 20–30%, poor > 30% (Jamieson et al. 1991).

Willmott (1981, 1982) developed the index of agreement, which is used especially for validating prediction models for the leaf area index (LAI) and above ground biomass (AGB) parameters. The index of agreement (d) is expressed as:

$$d = 1 - \frac{\sum_{i-1}^{n}\left(Observed_i - Simulated_i\right)^2}{\sum_{i-n}^{n}\left(\left|Observed_i - MeanObserved\right| + \left|Simulated_{i-} - MeanObserved\right|\right)^2}$$

Table 4 Results of scenario analysis of water response of crops grown in the winter wheat–mungbean–cotton cropping system assuming conditions with different irrigation water availability

Scenario	Unit	Baseline scenario			Medium water stress			High water stress			Very high water stress		
Crop		Winter wheat	Mungbean	Cotton	Winter wheat	Mung-bean	Cotton	Winter wheat	Mungbean	Cotton	Winter wheat	Mungbean	Cotton
Access to irrigation water	N. A	Full	Full	Full	Limited	Limited	Limited	Limited	Limited	Limited	Limited	No	Limited
Fertilizer application	NA	High	High	High	High	High	High	High	High	High	Low	No	Low
Groundwater level	NA	Shallow	Shallow	Shallow	Medium	Medium	Medium	Deep	Deep	Deep	Below 3 m	Below 3 m	Below 3 m
Irrigation amount, total	(mm)	464	200	497	278	120	298	185	80	198	92	0	99
Amount, % of 'normal'	(%)	100	100	100	60	60	60	40	40	40	20	0	20
Number of irrigations	Counting	8	4	6	4	2	4	3	1	3	2	0	2
Fertilizer amount	kg N ha^{-1}	180	30	200	180	30	200	180	30	200	100	0	125
Number of fertilizations		3	1	3	3	1	3	3	1	3	2	0	2
Type of fertilizer		Urea, NH_4NO_3	Urea	Urea, NH_4NO_3	Urea, NH_4NO_3	Urea	Urea, NH_4NO_3	Urea, NH_4NO_3	Urea	Urea, NH_4NO_3	Urea, NH_4NO_3	–	Urea, NH_4NO_3
Groundwater table		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	X	X	X
GW-level	(m b.s.)	1.0–2.0	1.0–2.0	1.0–2.0	1.8–2.5	1.8–2.5	1.8–2.5	> 3.00	> 3.00	> 3.00	/	/	/
Yield:	kg ha^{-1}	5202	1450	3353	3586	1195	1765	3479	1027	999	2051	0	324
AGB:	kg ha^{-1}	12689	4104	9062	8840	2987	5069	8618	2567	4802	5120	0	4381
Water stress		–	–	–	+	+	+	+	+	+	+	NA	+
Salinity stress		–	–	–	–	–	–	+	+	+	+	NA	+

m b.s. the meter below the surface: Low, medium and high water stress assumes a reduction of irrigation water applications of respectively of 80%, 60% and 40% from the amounts in the baseline scenario

Results and Discussion

Rotation Model in CropSyst

The CropSyst crop modules previously developed for the region to simulate irrigated cotton cv. Khorezm-127 (Sommer et al. 2008) and WW cv. Kupava (Djumaniyazova et al. 2010) growth and yield. These two modules were successfully developed for a sole cropping but they served as the basis to model the triple rotation (WW–Mungbean–Cotton) as a single cropping system. Developed the modules included default parameters as well as fine-tuned plant-physiological and phenological parameters for both crops as well as default and calibrated plant-physiological and phenological parameters for summer mungbean (Table 3). Yet, under the present study, several parameters needed to be adapted to reflect the conditions in the study years during which experimental data were collected. This resulted in another fine-tuning of plant-physiological and phenological parameters for irrigated WW cv. Krandoradskaya-99 in the rotation system examined. These parameters included: (i) the evapotranspiration crop coefficient at full-canopy that was decreased from 1.1 to 1.0, (ii) maximum expected leaf area index (LAI)—decreased from 7.0 to 5.0 m^2 m^{-2}, (iii) specific leaf area (SLA)—decreased from 20 to 15 m^2 kg^{-1}, (iv) unstressed harvest index (HI)—from 0.44 to 0.41; and (v) accumulated growing degree days (GDD) from seeding to emergence and flowering that were increased from 94 to 95 °C days and from 507 to 510 °C days respectively (Table 3). Similar adjustments were needed for fine tuning the irrigated cotton cv. Khorezm-127 in the treble crop rotation. Therefore, the biomass-transpiration coefficient (kg m^{-2} kPa m^{-1}) was increased from 8.1 to 8.5, the PAR use efficiency—from 2.0 to 2.5 g MJ^{-1}, the accumulated growing degree days (GDD) from seeding to emergence and maturity—from 110 to 170 °C days and from 1630 to 1680 °C days respectively. The unstressed HI was reduced from 0.41 to 0.37 (Table 3).

For the parameterization of the mungbean module, previously not parameterized for the irrigated conditions of the study region, the canopy growth was simulated based on LAI development. CropSyst considered the impact of high, detrimental temperature during anthesis, by calculating a harvest index (HI) reduction factor (0–1). The summer mungbean phenology was derived from in situ observations. Base temperature, cut-off temperature, optimal mean daily temperature for growth, the biomass-transpiration coefficient, the radiation use efficiency and the leaf/stem partition coefficient were calibrated manually by fitting the simulated LAI, AGB and grain yield to experimental data from 2011 (Table 3). Thermal times, expressed as GDD from planting to emergence, flowering, grain filling, and maturity, were adjusted also to match the empirical evidence. Unstressed HI data was taken from the trial (Table 3).

Since the fields in Khorezm, suffer from soil salinity and/or shallow (saline) groundwater, CropSyst's soil salinity and shallow groundwater routine were enabled. Shallow groundwater dynamics were entered in the model as observed on-site. Various model parameters, including the leaf water potential at the onset of stomatal closure or at wilting, were kept in the model as defaults (Table 3). Soil water simulation dynamics during the rotation matched well with measured irrigation time (Fig. 2).

Model Calibration and validation

Model Calibration

Observed and simulated LAI values matched well during the WW vegetation period with acceptable index of agreement (d = 0.92), except for the 179-day after planting (DAP179) when the model estimated an advance in crop development, and at DAP217 when the LAI-peak was underestimated with a difference of 0.4 m^2 m^{-2} (Fig. 1). On the other hand, the observed maximum LAI of 4.8 m^2 m^{-2} was close to the previously reported 4.2 m^2 m^{-2} of wheat-LAI (Singh et al. 2008), albeit still less than other findings (Wolf et al. 1996; Ventrella and Rinaldi 1999), that had reported LAI ranging from 6.3 to 6.8 m^2 m^{-2}.

The empirical (12.62 Mg ha^{-1}) and simulated AGB (13.58 Mg ha^{-1}) at WW harvest matched well as did the AGB development during the season (Fig. 3, 5) as evidenced by a RMSE = 0.97 Mg ha^{-1} (RRMSE = 8%) and an index of agreement (d = 0.98).

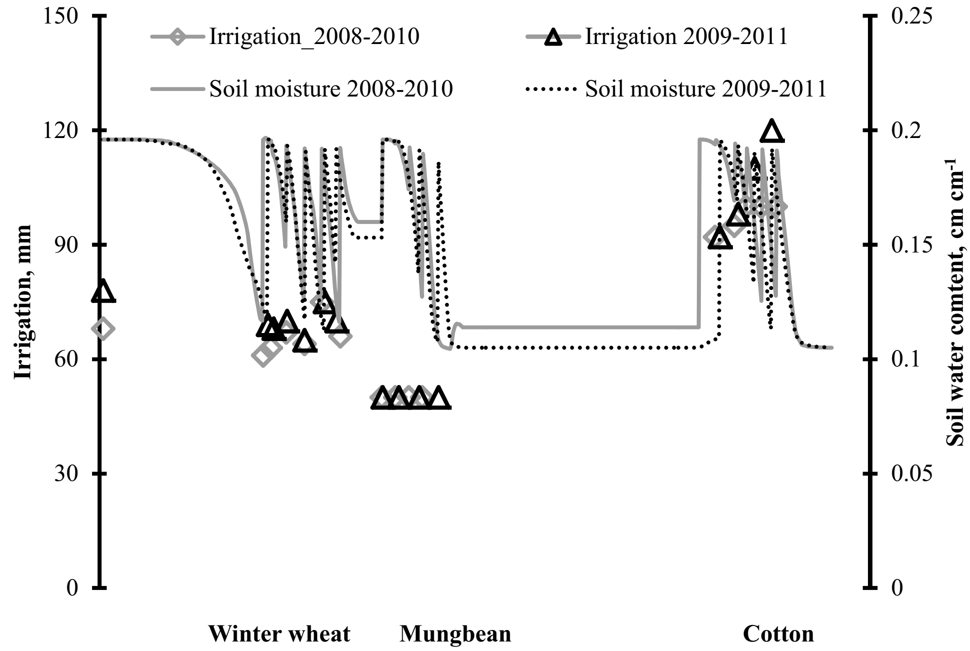
The observed and simulated grain yields of WW were 5.97 and 5.57 Mg ha^{-1} respectively with a RMSE of 0.40 Mg ha^{-1} (RRMSE = 7%). The corresponding RMSE and RRMSE for AGB and grain yield are very acceptable.

During the Mungbean-parameterization in the first calibration year 2009, the observed and simulated mungbean LAI and AGB matched well throughout the vegetation period (Fig. 3). The observed peak LAI of 2.4 m^2 m^{-2} occurred at DAP51. The empirical maximum-LAIs of irrigated mungbean in India had ranged from 2.4 to 3.8 m^2 m^{-2} (Yadav and Singh 2014) and were therefore in line with the current findings. However, higher maximum LAIs, ranging from 3.1 to 4.9 m^2 m^{-2} were previously reported as well (Sengupta et al. 2011; Samant 2014). Index of agreement for leaf area index was very acceptable (d = 0.97).

Observed and simulated AGB values at Mungbean-harvest amounted to 4.22 and 4.19 Mg ha^{-1} respectively with a RMSE = 0.03 Mg ha^{-1} and RRMSE = 1% (Fig. 5). Index of agreement for AGB was d = 1.00.

They thus showed a close match as did the observed and simulated grain yields of mungbean (1.33 and 1.45 Mg ha^{-1}

Fig. 2 Measured irrigation amount in millimeters (points) and simulated soil water in centimeters (line) of three crops in the treble "winter wheat (WW)–mung bean (MB)–cotton (Cot)" rotation (for two cycles of the rotation)



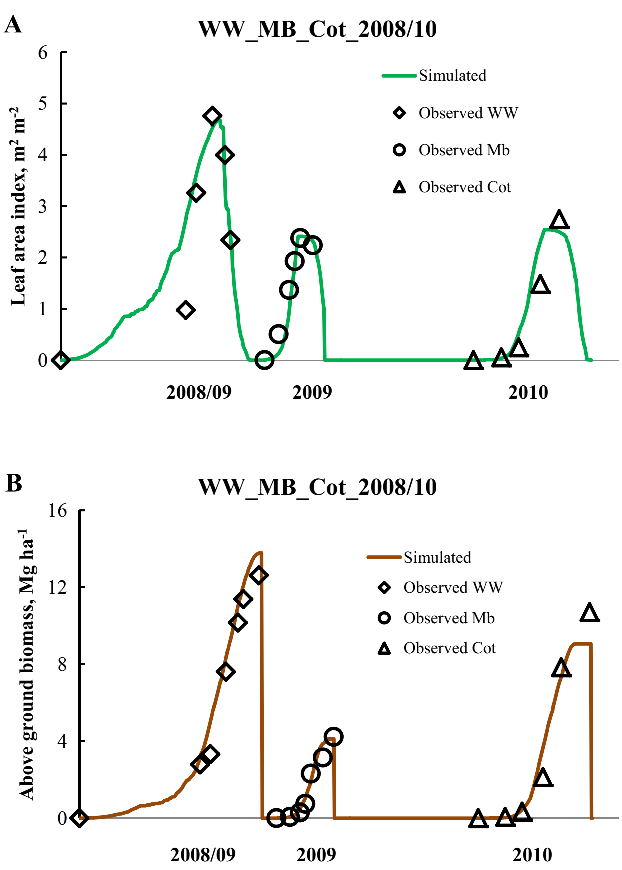


Fig. 3 Observed (points) and simulated (line) leaf area index (**a**) and aboveground biomass (**b**) of three crops in the treble "winter wheat (WW)–mungbean (MB)–cotton (Cot)" rotation (model parameterization)

respectively with an RMSE = 0.12 Mg ha^{-1} (RRMSE = 9%). The corresponding RMSE and RRMSE for AGB and grain yields were acceptable also.

The cotton LAI in the first model parameterization year (2010) was slightly overestimated at DAP96 but underestimated later (DAP123, Fig. 3). The peak LAI (2.8 m^2 m^{-2}) was observed at cotton bolls formation (DAP123), which is in line with previous findings (e.g. Sommer et al. 2008; Milroy and Bange 2003; Peng and Krieg 1991) that maximum LAIs of cotton ranging between 2.5 to 3.0 m^2 m^{-2}. Index of agreement for Leaf area index was d = 1.00.

The observed and simulated AGB at cotton maturity amounted to 10.70 and 9.10 Mg ha^{-1} with an RMSE = 1.60 Mg ha^{-1} (RRMSE = 15%), whilst the observed and simulated seed cotton yields matched with 3.16 and 3.37 Mg ha^{-1} with RMSE = 0.21 Mg ha^{-1} (RRMSE = 6%) and d = 0.99 quite well.

Model validation

The model estimated an earlier WW-LAI development between DAP191 - DAP205 than observed during the 2009/10 seasons (Fig. 4). Furthermore, the observed peak LAI of 5.1 m^2 m^{-2} was underestimated by the model with a difference of 0.6 m^2 m^{-2}(d = 0.81) (Fig. 4). Yet, the observed and simulated WW-AGB at crop harvest were 10.78 and 12.21 Mg ha^{-1} respectively with a RMSE = 1.43 Mg ha^{-1} (RRMSE = 13%) and d = 0.94 matched reasonably well (Fig. 5). Consequently, the observed and simulated WW-grain yields were close 5.12 and 5.01 Mg ha^{-1} with a RMSE = 0.11 Mg ha^{-1} (RRMSE = 2%).

In the second model validation year (2009–2010), the LAI values for mungbean were slightly underestimated at DAP15 and DAP27 due to a reduced LAI development estimated by the model (Fig. 4). The LAI was underestimated at its peak (DAP51) with a difference of 0.56 m^2 m^{-2} compared to the empirical LAI value of 2.63 m^2 m^{-2}. The early season AGB was slightly underestimated at DAP15 and DAP27, but the observed and simulated AGB at crop harvest was very close 3.29 and 3.45 Mg ha^{-1} (RMSE = 0.17 Mg ha^{-1}; RRMSE = 5%; d = 1.00) (Figs. 4, 5). Also in this second validation year, the simulation of mungbean grain yields matched well the empirical findings as evidenced by observed and simulated grain yields of 1.20 and 1.18 Mg ha^{-1} with a RMSE = 0.07 Mg ha^{-1} (RRMSE = 5%).

During model validation, the cotton LAI was slightly underestimated at DAP54, DAP62, and DAP107. At boll formation (DAP107) the observed LAI value of 2.7 m^2 m^{-2} was underestimated by the model, albeit with a difference of 0.2 m^2 m^{-2} only. Compared to the observed AGB of 10.74 Mg ha^{-1}, the simulated AGB of 9.59 Mg ha^{-1} with a RMSE = 1.16 Mg ha^{-1} (RRMSE = 11%) and d = 0.99 matched again acceptable well. The resulting observed and simulated seed-lint yields of cotton showed therefore with 3.33 and 3.55 Mg ha^{-1} also a very good match as confirmed by a RMSE = 0.22 Mg ha^{-1} (RRMSE = 7%). Index of agreement for Leaf area index and above ground biomass were 0.97 and 0.99 respectively. The simulations for parameterization and validation years overall comparison of observed and simulated leaf area index (LAI) and above ground biomass (AGB) showed excellent and good fit as reported (Loague and Green 1991; Jamieson et al. 1991) for three crops (Fig. 5).

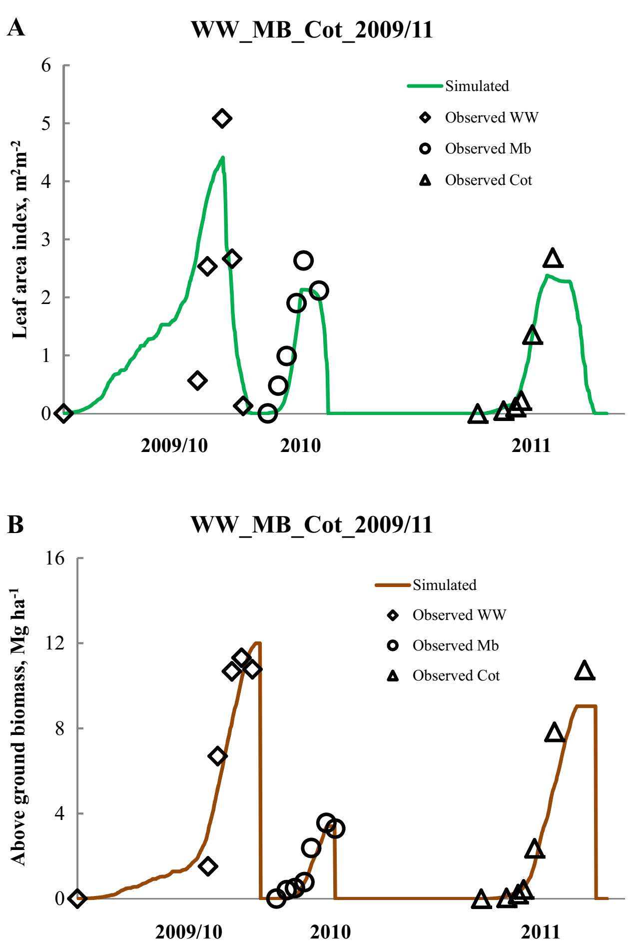


Fig. 4 Observed (points) and simulated (line) leaf area index (**a**) and aboveground biomass (**b**) of three crops in the treble "winter wheat (WW)–mungbean (MB)–cotton (Cot)" rotation (model validation)

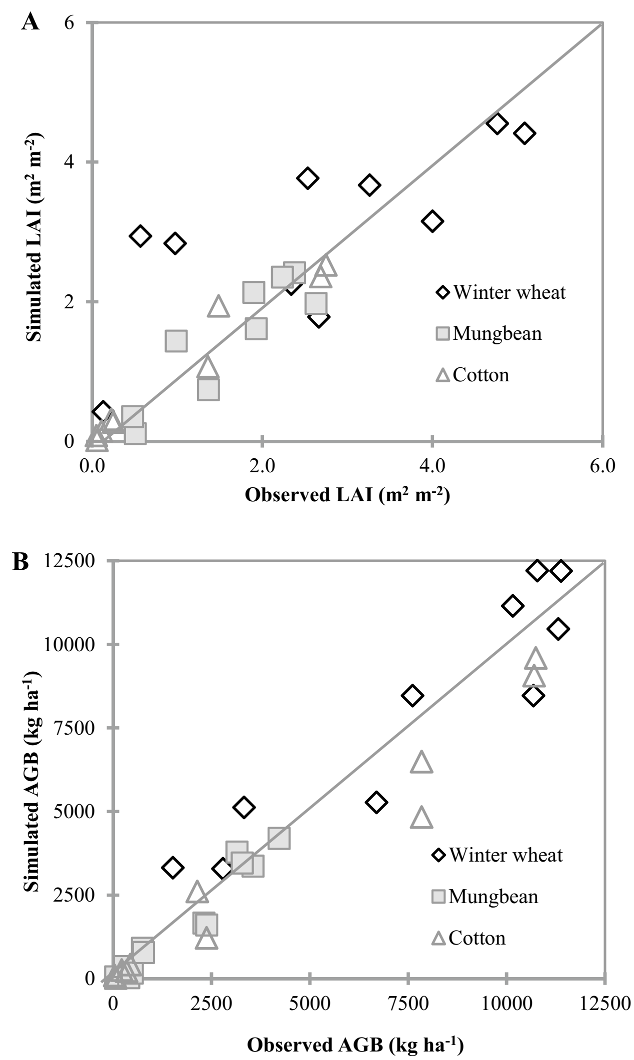


Fig. 5 Overall comparison of observed and simulated leaf area index (LAI) and above ground biomass (AGB) the winter wheat–mungbean–cotton cropping system

Scenario Analyses

Fertility Management Scenarios

Following the successful parameterization and validation of the CropSyst model, it could be used for the simulation of crop growth and yields of all crops in the WW–summer mungbean–cotton cropping system. While assuming different soil textures and SOM levels, the findings showed that the model could capture the effects of SOM on growth and yields of all three crops. Hence, higher levels of SOM increased AGBs for all three crops in the treble rotation (Fig. 6).

This AGB-increase amounted to 1.41 Mg ha^{-1} for WW, 0.72 Mg ha^{-1} for mungbean and 0.56 Mg ha^{-1} for cotton. Similarly to AGB, when assuming higher soil fertility (HSF) conditions, higher yields were simulated for WW grain and seed cotton. Therefore, under HSF yields increased with 0.58 Mg ha^{-1} for WW grain and 0.21 Mg ha^{-1} for cotton. Mungbean grain yields were not affected by different SOM contents (1.45 and 1.45 Mg ha^{-1} under LSF and HSF (Fig. 7).

This was as expected since the leguminous mungbean had been able to fix atmospheric N_2, which substantially contributed to satisfy crop N-demands as previously reported (Sharma et al. 2007; Dudejai and Duhan 2005; Dayathilake et al. 2001).

Irrigation Water Management Scenarios

Baseline scenario The years of 2008–2010 were assumed being representative for a situation with three consecutive seasons without water-stress and thus for cropping conditions resembling full irrigated fields according to state recommendations. In this case, WW, mungbean, and cotton received 464, 200 and 497 mm of irrigation water respectively. When assuming in addition the application of the state recommended rates of chemical fertilizers ($N_{180}P_{130}K_{100}$ kg ha^{-1} for winter wheat, $N_{30}P_{120}K_{100}$ kg ha^{-1} for mungbean and $N_{200}P_{140}K_{100}$ kg ha^{-1} for cotton), the simulated crop yields amounted to 5.20 Mg ha^{-1} of WW grain, 1.45 Mg ha^{-1} of mungbean grain and 3.35 Mg ha^{-1} of seed-lint cotton (Table 4).

Low water stress (LWS) Assuming 80% of irrigation water supply compared to the recommended amounts, but the recommended application of chemical fertilizers for all crops in the treble rotation, the grain yield of WW remained similar compared to the baseline scenario. The mungbean and cotton yields, however, were lower and reduced by 17 and 31% respectively (data are not shown).

Medium water stress (MWS) Assuming limited access to irrigation water (e.g. 60% of the recommended water supply), the AGB and yields of all three crops decreased

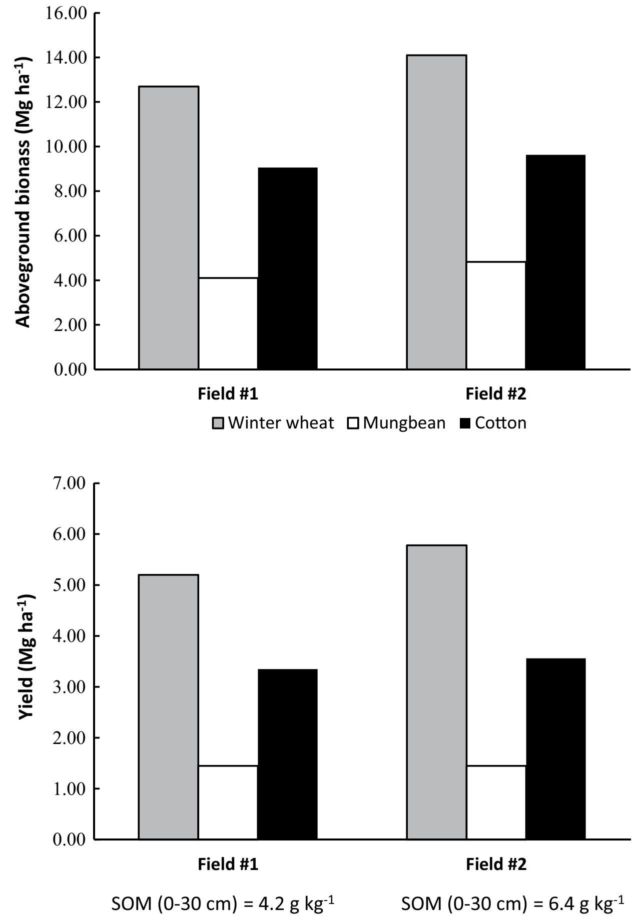


Fig. 6 Model-based aboveground biomass (ABG) and crops yields with different soil organic matter contents (SOM) under the winter wheat–mungbean–cotton cropping system

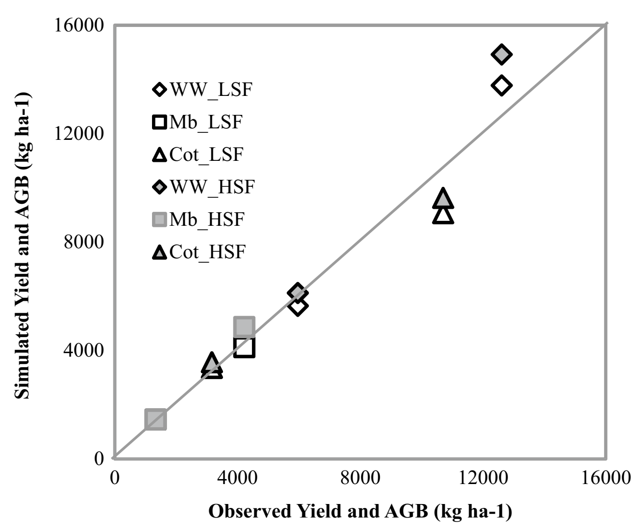


Fig. 7 Simulated and observed aboveground biomass (ABG) and crops yields with different soil organic matter contents (SOM) under the winter wheat–mungbean–cotton cropping system

(Table 4). Cotton AGB and seed-lint yield were lower by 44% and 47% respectively. Since cotton is considered drought tolerant, it is should not be sensitive to water shortage in all growth stages (Loka et al. 2011). Yet, limited water supply during reproductive development can drastically lower yields (De Kock et al. 1993). The same was true for WW (30% reduction for AGB and 31% for grain yields) compared to the baseline scenarios. The sensitivity of WW grain yields to water shortage/drought depends on the severity of stress and the development/growth stage of WW (Giunta et al. 1993). Hence, WW grains yield had substantially been reduced when the crop was not irrigated tillering (S2) and/or flowering (S6) stages, and conversely, if crop faced drought only at tillering or anthesis stage, WW yields can still be expected. The least reduction in AGB and yield under MWS was estimated for mungbean (27 and 18% respectively). Most of this reduction in mungbean yield under medium water stress was likely due to the lower transpiration rates that resulted in increased water use efficiency of the crop, allowing the application of less irrigation water (Webber et al. 2006).

High water stress (HWS) Assuming 40% water supply compared to the baseline conditions without water stress, the model simulated a substantial drop in AGB and yields of all three crops in the treble rotation (Table 4). Decreases in AGB and yields were accordingly 32 and 33% for winter wheat and 37 and 29% for mungbean compared to fully irrigated fields. Similarly to the assumption of medium water stress, the seed-lint yield of cotton was affected most among all crops (70% reduction) in the treble rotation. Consequently, crop yields were substantially reduced under HWS.

Very high water stress (VHWS) Assuming an extremely dry year scenario, ca. 20% of irrigation supply occurred to wheat and cotton. Under VHS, summer mungbean was not cropped since the imposed allocation of available irrigation water resulted in irrigation of wheat and cotton only. Compared to the HWS scenario, the WW and cotton yields dropped even further. Given that with an absence of irrigation events, groundwater in the region immediately drops (Ibrakhimov et al. 2011) also this source cannot be exploited anymore under VHWS conditions. This leads to drastic yield losses as previously reported (Bekchanov et al. 2014),and simulated as well: WW grain by 2.05 Mg ha^{-1} and cotton yields by 0.32 with a drop thus of 61% and 90% compared to the reference scenario.

An archive of previous findings underlined that irrigation water use in the study region is huge and often resembles a case of over-applying, leading consequently to a high and rapid rise of the groundwater levels (Awan et al. 2012; Forkutsa et al. 2009): sometimes even up to dangerous levels meaning being a major driver of soil salinization. Assuming a 20% reduction in the water supply (MWS), it seems that consequently groundwater levels were only marginally affected and hence crops could tap into this source to support crop water demand even though small yield declines can be expected with mungbean and cotton cultivation. Yet, when assuming further reductions in water supply, severe drops in groundwater levels are a consequence up to levels outside the rooting zone and hence leading irrigation water declines to drastically reduce growth and yields of all three crops. Consequently, when assuming conditions resembling extremely dry years, that occurred e.g. in the study region during 2001–2011 at least three times (Bekchanov et al. 2014), the limited access to irrigation water leads to drastic groundwater drops and reduced crop yields, which concur with reality as well (Forkutsa et al. 2009).

Conclusions

The CropSyst model's crop rotation module was used to simulate productivity in the winter wheat–summer mungbean–cotton cropping system under irrigated agro-ecological conditions in Uzbekistan. Previously, the CropSyst had been successfully applied in Uzbekistan for irrigated cotton and winter wheat as as a single cropping. The CropSyst was further fine-tuned using winter wheat and cotton data from the experiment with the treble crop rotation carried out in the Khorezm region of Uzbekistan aimed to increase the model accuracy and precision. Additionally, the model was separately parameterized and verified using data set from the same experiment for short duration mung bean grown as a summer crop in the treble crop rotation. The fits between the simulated and empirical values for the various parameters examined provided the necessary confidence for using the model in a number of scenario analysis.

The model was able to distinguish the impact of different soil fertility, particularly SOM and exchangeable potassium contents in soil, on crop AGB and yield. Compared to the soil with lower SOM (4.2 g kg^{-1}), the model estimated yields of winter wheat and cotton were higher for 15 and 6% respectively in the soil with higher SOM (6.4 g kg^{-1}). The mungbean grain yields were not affected by differing SOM concentrations which could be due to the nitrogen-fixing ability of the crop.

Also, scenario analysis showed the possibility of reduced irrigation (up to 80% of full irrigation) of winter wheat with no grain yield penalty. Deficits of irrigation (40 and 20% of 'normal', respectively) could decrease the grain yields up to 61%. However, the scenario analysis confirmed that cotton—a major crop in the country—is sensitive to deficits of irrigation. Even though groundwater is basically very shallow in the Khorezm region (the water table is higher than two meters which is the case in normal years), full irrigation of cotton according to crop demand helps achieving high yields of the crop. Compared to full irrigated fields, the cotton yields could decrease by 47, 70 and 90% under accordingly 60, 40 and 20% of water supply. The model also estimated the mungbean yields reduction up to 29% in dry years (60 and 40% of 'normal', respectively). When ground water level below 3 meters in extremely dry year mungbean could not produce any yield. Thus, in irrigation water scarcity years with groundwater level below two meters, a substantial yield decrease can be expected. The developed model could be useful to increase the understanding the nexus of food, energy and water in Khorezm and comparable regions of Central Asia, and to inform decision-making more sustainable use of available water resources.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Abid, M., Scheffran, J., Schneider, A. U., & Ashfaq, M. (2015). Farmers' perceptions of and adaptation strategies to climate change and their determinants: The case of Punjab province, Pakistan. *Earth System Dynamics, 6,* 225–243. https://doi.org/10.5194/esd-6-225-2015.

Akramkhanov, A. (2005). The spatial distribution o f soil salinity: Detection and prediction. *ZEF Series in Ecology and Development No. 32*. Bonn: University of Bonn.

Akramkhanov, A., Kuziev, R., Sommer, R., Martius, C., Forkutsa, O., & Massucci, L. (2012). Soils and soil ecology in Khorezm. In C. Martius (Ed.), *Cotton, Water, Salts, and Soums. Economic and Ecological Restructuring in Khorezm, Uzbekistan* (pp. 37–58). New York: Springer.

Awan, U. K., Tischbein, B., & Martius, C. (2012). Combining hydrological modeling and GIS approaches to determine the spatial distribution of groundwater recharge in an arid irrigation scheme. *Springer Verlag Irrigation Science, 31*(4), 793–806. https://doi.org/10.1007/s00271-012-0362-0.

Babadjanova, Sh. K., Eshchanov, R. A., Ibragimov, N. M., Ruzimov, J. Sh. (2012). Effects of inter-row width on mung bean productivity on irrigated alluvial soil of the desert zone of Uzbekistan, (in Rus). In *Agrarian science—agriculture collection of articles in 2 book. Proceedings of VII international scientific and practical conference 2–3 February 2012*. Barnaul RIO. AGAU (pp. 283–285).

BBCH Monograph 2, (2001). Growth stages of mono- and dicotyledonous plants. In Uwe Meier (Ed.) *Federal Biological Research Centre for Agriculture and Forestry Edition* (pp. 158).

Bekchanov, M., Lamers, J. P. A., & Martius, C. (2014). Coping with water scarcity in the irrigated lowlands of the lower Amudarya basin, Central Asia. In J. P. A. Lamers, et al. (Eds.), *Restructuring land allocation, water use, and agricultural value chains. Technologies, policies, and practices for the lower Amudarya region. V & R unipress* (pp. 199–216). Goettingen: Bonn University Press.

Burmester C.H., Reeves D.W., and Motta A.C.V., (2002). Effect of crop rotation/tillage systems on cotton yield in the Tennessee Valley area of Alabama, 1980–-2001. In E. van Santen (Ed.) *Making Conservation Tillage Conventional: Building a Future on 25 Years of Research. Proceedings of 25th Annual Southern Conservation Tillage Conference for Sustainable Agriculture. Auburn, Special Report no. 1.* (pp 354–357). Alabama: Auburn University.

Conrad, C., Schönbrodt-Stitt, S., Löw, F., Sorokin, D., & Paeth, H. (2016). Cropping intensity in the Aral Sea Basin and its dependency from the runoff formation 2000–2012. *Remote Sensing, 8,* 630. https://doi.org/10.3390/rs8080630.

Constable, G. A., Rochester, I. J., & Daniells, I. G. (1992). Cotton yield and nitrogen requirement are modified by crop rotation and tillage method. *Soil & Tillage Research, 23,* 41–59.

Cook, R. L., & Ellis, B. G. (1987). *Soil Management: A worldview of conservation and production* (pp. 152–170). Singapore: John Wiley & Sons. New York.

Cooper, J. L. (1999). A grower survey of rotations used in the New South Wales cotton industry. *Australian Journal of Experimental Agriculture, 39,* 743–755.

Dayathilake, G. A., Subasinghe, S., & Senaratne, R. (2001). N fixation potential of cowpea and mungbean lines and its effects on succeeding maize crop. *Tropical Agricultural Research and Extension, 4,* 6–9.

De Kock, J., de Bruyn, L. P., & Human, J. J. (1993). The relative sensitivity to plant water stress during the reproductive phase of upland cotton, *Irrig. Sci*. 11, 239–244.De Kock, J., de Bruyn L.P., and Human J.J. 1993. The relative sensitivity to plant water stress during the reproductive phase of upland cotton. *Irrigation Science, 14,* 239–244.

Devkota, M., Martius, C., Lamers, J. P. A., Sayre, K. D., Devkota, K. P., & Vlek, P. L. G. (2013). Tillage and nitrogen fertilization effects on yield and nitrogen use efficiency of irrigated cotton. *Soil and Tillage Research, 134,* 72–82.

Djumaniyazova, Y., Sommer, R., Ibragimov, N., Ruzimov, J., Lamers, J. P. A., & Vlek, P. L. G. (2010). Simulating water use and N response of winter wheat in the irrigated floodplains of Northwest Uzbekistan. *Field Crops Research, 116,* 239–251.

Dudejai, S. S., & Duhan, J. S. (2005). Biological nitrogen fixation research in pulses with special reference to mungbean and urdbean. *Indian Journal of Pulses Research, 18,* 107–118.

Forkutsa, I., Sommer, R., Shirokova, Y., Lamers, J. P. A., Kienzler, K., Tischbein, B., et al. (2009). Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: I. Water dynamics. *Irrigation Science, 27*(4), 331–346.

Giunta, F., Motzo, R., & Deidd, M. (1993). Effect of drought on yield and yield components of Durum Wheat and triticale in a Mediterranean environment. *Field Crops Research, 33,* 399–409.

Haitbayeva, J. U., (2019). Effects of mineral fertilizer rates to productivity of winter wheat in conditions of irrigated meadow alluvial soils of Khorezm region Uzbekistan (In Russian). Actual problems of modern science. Moscow. No. 3. pp. 129–133 (06.00.00. No.5).

Hulugalle, N., & Scott, F. (2008). A review of the changes in soil quality and profitability accomplished by sowing rotation crops after cotton in Australian Vertosols from 1970 to 2006. *Australian Journal of Soil Research, 42,* 173–190.

Ibrakhimov, M., Khamzina, A., Forkutsa, I., Paluasheva, G., Lamers, J. P. A., Tischbein, B., et al. (2007). Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in the Khorezm region.Uzbekistan, Aral Sea Basin. *Irrigation Science, 21,* 219–236.

Ibrakhimov, M., Martius, C., Lamers, J. P. A., & Tischbein, B. (2011). The dynamics of groundwater table and salinity over 17 years in Khorezm. *Agricultural Water Management, 101*(1), 52–61.

Jacovides, C. P., & Kontayiannis, H. (1995). Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management, 27,* 365–371.

Jamieson, P. D., Porter, J. R., & Wilson, D. R. (1991). A test of computer simulation model ARC-WHEAT1 on wheat crops grown in New Zealand. *Field Crops Research., 27,* 337–350. https://doi.org/10.1016/0378-4290(91)90040-3

Kienzler, K. M., Djanibekov, N., & Lamers, J. P. A. (2011). An agronomic, economic and behavioral analysis of N application to cotton and wheat in post-Soviet Uzbekistan. *Agricultural Systems*. https://doi.org/10.1016/j.agsy.2011.01.005.

Loague, K., & Green, R. E. (1991). Statistical and graphical methods for evaluating solute transport models overview and application. *Journal of Contaminant Hydrology, 7,* 51–73.

Loka D.A., Oosterhuis D.M., and Ritchie G.L., (2011). Water deficit stress in cotton, in *Stress Physiology in Cotton*, Ed by D.M. Oosterhuis (The Cotton Foundation, Memphis, TN.) p. 37–71.

Mandelbaum, Michael M. (1994). *Central Asia and the World: Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan* (p. 251). New York: Council on Foreign Relations Press. vii.

Milroy, S. P., & Bange, M. P. (2003). Nitrogen and light response of cotton photosynthesis and implications for crop growth. *Crop Science, 43,* 904–913.

Peng, S., & Krieg, D. R. (1991). Single leaf and canopy photosynthesis response to plant age in cotton. *Agronomy Journal, 83,* 704–708.

Samant, T. K. (2014). Evaluation of growth and yield parameters of green gram (*Vigna radiate* L.). *Agriculture Update, 9,* 427–430.

Sengupta, K., Banik, N. C., Bhui, S., & Mitra, S. (2011). Effect of Brassinolide on growth and yield of summer green gram crop. *Journal of Crop and Weed, 7,* 152–154.

Sharma, P., Sekhon, H. S., Veena, K., & Singh, G. (2007). Biological nitrogen fixation in mungbean: facts and findings. *Acta Horticulturae (ISHS), 752,* 597–602.

Singh, A. K., Tripathy, R., & Chopra, U. K. (2008). Evaluation of CERES-Wheat and CropSyst models for water-nitrogen interactions in wheat crop. *Agricultural Water Management, 95,* 776–786.

Sommer, R., Kienzler, K., Conrad, C., Ibragimov, N., Lamers, J., Martius, C., et al. (2008). Evaluation of the CropSyst model for simulating the potential yield of cotton. *Agronomy for Sustainable Development, 28,* 345–354.

Stockle, C. O., Donatelli, M., & Nelson, R. (2003). CropSyst, a cropping systems simulation model. *European Journal of Agronomy, 18,* 289–307.

Ventrella, D., & Rinaldi, M. (1999). Comparison between two simulation models to evaluate cropping systems in southern Italy. Yield response and soil water dynamics. *Agricoltura Mediterranea, 129,* 99–110.

Webber, H. A., Madramootoo, C. A., Bourgault, M., Horst, M. G., Stulina, G., & Smith, D. L. (2006). Water use efficiency of common bean and green gram grew using alternate furrow and deficit irrigation. *Agricultural Water Management, 86,* 259–268.

Willmott, C. J. (1981). On the validation of models. *Physical Geography, 2*(2), 184–194.

Willmott, C. J. (1982). Some comments on the evaluation of model performance. *Bulletin American Meteorology Society, 63*(11), 1309–1313.

Wolf, J., Evans, L. G., Semenov, M. A., Eckersten, H., & Iglesias, A. (1996). Comparison of wheat simulation models under climate change. I. Model calibration and sensitivity analyses. *Climate Research, 7,* 253–270.

Wright, A. L., Hons, F. M., & Matocha, J. E., Jr. (2005). Tillage impacts on microbial biomass and soil organic carbon and nitrogen dynamics of corn and cotton rotations. *Applied Soil Ecology, 29,* 85–92.

Yadav, S., & Singh, B. N. (2014). Effect of irrigation schedules and planting methods on growth, productivity and WUE of green gram (*Phaseolus radiate* L.) under rice-wheat-green gram cropping system. *Plant Archives, 14,* 211–213.

Zhonghu, H. and Alain Bonjean, P. A., (2010). Cereals in China, *Mexico, D.F.* CIMMYT.