MODELING THE EFFECTS OF CROP ROTATION AND TILLAGE ON SUGARBEET YIELD AND SOIL NITRATE USING RZWQM2

M. J. Anar, Z. Lin, L. Ma, A. Chatterjee

HIGHLIGHTS

- Four crop growth modules in RZWQM2 were calibrated for four sugarbeet rotation sequences.
- Sugarbeet following wheat had a slightly higher yield (3% to 6.5%).
- Moldboard plow increased sugarbeet yield by 1% to 2%.
- The difference in N losses under different crop rotations and tillage operations was negligible.

ABSTRACT. *Sugarbeet (*Beta vulgaris*) is considered to be one of the most viable alternatives to corn for biofuel production as it may be qualified as the feedstock for advanced biofuels (reducing greenhouse gas emission by 50%) under the Energy Independence and Security Act (EISA) of 2007. Because sugarbeet production is affected by crop rotation and tillage through optimal use of soil water and nutrients, simulation of these effects will help in making proper management decisions. In this study, the CSM-CERES-Beet, CSM-CERES-Maize, CROPSIM-Wheat, and CROPGRO-Soybean models included in the RZWQM2 were calibrated against experimental field data of crop yield, soil water, and soil nitrate from the North Dakota State University Carrington Research Extension Center from 2014 to 2016. The models performed reasonably well in simulating crop yield, soil water, and nitrate (rRMSE = 0.055 to 2.773, d = 0.541 to 0.997). Simulation results identified a non-significant effect of crop rotation on sugarbeet yield, although sugarbeets following wheat resulted in 3% to 6.5% higher yields compared to other crops. Net mineralization and N uptake rates were slightly higher when sugarbeets followed wheat compared to the other crops. Seasonal N and water mass balances also showed lower N and water stresses when sugarbeets followed wheat. The effects of tillage operations on sugarbeet yield were also non-significant. The difference in the N losses to runoff and drainage from the sugarbeet fields under different crop rotations and tillage operations was negligible. As sugarbeet production may be expanded into nontraditional planting areas in the Red River Valley due to potential demand for biofuel production, our findings will help to assess the associated environmental impacts and identify suitable crop rotations and management scenarios in the region.*

Keywords. *Biofuel, Crop rotation, RZWQM2, Sugarbeet, Tillage.*

Bioenergy crops are renewable energy sources due to their capabilities of improving national energy security and reducing greenhouse gas (GHG) emissions. The Renewable Fuel Standard of the U.S. Energy Independence and Security Act (EISA) of 2007 has set a national target of 136 billion liters of renewable fuels by 2022, of which 61 billion liters are expected from biofuels (USEPA, 2010). Under the EISA, advanced biofuels are classified as non-grain-based biofuels derived from lignocellulosic biomass such as timber chips and perennial grasses, sugar crops such as sugarcane and sugarbeets, and waste materials including crop residues and urban waste (U.S. Congress, 2007). Currently, the U.S. is still reliant on corn, which is a grain-based source of bioethanol, but corn production alone is not enough to meet the renewable fuel targets. Furthermore, the use of corn for biofuel production has a significant impact on food supply (Maung and Gustafson, 2011).

Energy beets, a variety of sugarbeet (*Beta vulgaris*), are being considered for biofuel production because of their high sugar content, which could potentially produce twice as much ethanol per acre compared to other feedstocks (corn or cellulose) (Shapouri et al., 2006; Panella, 2010). Unlike conventional sugarbeets, energy beets are specialized non-food grade varieties grown mainly for industrial use, including bioenergy production (Maung and Gustafson, 2011; Kakani et

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al., 2012; Nahar and Pryor, 2013; Vargas-Ramirez et al., 2013). The largest region for sugarbeet (energy beet) production in the U.S. is the Red River Valley (RRV) and its vicinity in western Minnesota and eastern North Dakota, where 57% of the nation's total sugarbeets were produced in 2016-2017 (USDA, 2018). In 2011, sugarbeet production in the RRV region generated a direct economic impact of $1.7 billion (Bangsund et al., 2012). Sugarbeet production will continue to increase if several 20 million gallons per year sugarbeet processing plants for biofuel production are built in the region (Maung and Gustafson, 2011). Given the increasing economic and environmental impacts of sugarbeet production, it is important to identify the best agronomic management practices (i.e., crop rotation and tillage operations) associated with sugarbeet production.

Agronomic management practices, such as crop rotation and tillage, can play a significant role in sugarbeet growth and yield by maximizing profits through proper utilization of soil water and nutrients. Crop rotation is effective in suppressing certain diseases, pests, and weeds in sugarbeet (UNE, 2013). Tillage affects nutrient cycling by altering the soil structure and the decomposition of crop residues and soil organic matter (Katupitiya et al., 1997). However, crop rotation and tillage may also negatively impact sugarbeet yield if not carefully implemented, depending on other factors including soil moisture, fertility, compaction, plant residues, diseases, weeds, insects, or allelopathy (Havlin et al., 1990; Hao et al., 2001).

In most of the RRV region, sugarbeet production typically follows small grains, such as hard red spring wheat (HRSW) (*Triticum aestivum* L.), corn (*Zea mays*), or soybean (*Glycine max*) (Sims, 2004). Wheat generally produces a tremendous amount of residue that can reduce soil erosion and provide a protective barrier for the seedlings. It can also conserve soil moisture and increase soil organic matter (Sims, 2004). Corn produces less residue than wheat but more than that of soybean. Leguminous crops like soybean leave more nitrogen in the soil compared to other crops in the rotation (Hao et al., 2001), while the residues from both corn and wheat decompose slowly due to less water-soluble substances within wheat or corn and allow the addition of mineralized N during the later stages of the following crops in the rotation (Sims, 2004; Overstreet et al., 2007). However, if the nitrogen from the residue decomposition becomes available during the later state of sugarbeet growth, it may impact the quality of sugarbeet by increasing the impurities (Sims, 2004).

Several studies have reported the effects of crop rotation on sugarbeet yields in the RRV region. Sims (2004) reported slight positive or no effect of wheat on subsequent sugarbeet root yield and quality. He also observed negative effects of corn residue on sugarbeet yield, although the effect appeared not to be related to nitrogen (N) availability. On the other hand, Overstreet et al. (2007) observed a non-significantly greater yield of sugarbeet following corn compared to wheat or soybean. In their research, Smith and Dexter (1988) also reported reductions in both sugarbeet root yield and quality (recoverable sucrose per ton of beet) that was rotated after soybean compared to that after a small grain crop. Similarly, Soine and Severson (1975), Nordgaard et al. (1982), and Sims (2009) found little or no positive effect of prior soybean on sugarbeet root yield and quality in the RRV region.

Tillage may affect crop yields by altering soil physical, chemical, and biological properties. It affects soil bulk density, hydraulic conductivity, and penetration resistance, therefore affecting water infiltration, internal drainage, and aeration of the soil (Jabro et al., 2010). It may also affect plant population and weed, pest, and disease infestation. Reduced or conservation tillage with increased surface residues prevents loss of organic matter from the soil and may improve crop production (Havlin et al., 1990).

Interactive use of field experiments and ecosystem-level models can be useful in identifying the best agronomic practices for sustainable agriculture productivity and improved environmental quality. The models that are currently available to assess the impacts of agricultural management on water quality include CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Sharpley and Williams, 1990), NLEAP (Shaffer et al., 1991), and OPUS (Smith, 1992). However, these models are too simplistic in terms of simulating root zone processes and are limited to a narrow range of agricultural practices (Hanson et al., 1988). The Root Zone Water Quality Model (RZWQM2) was developed to address these concerns (Saseendran et al., 2007; Ma et al., 2012).

The process-based RZWQM2 has been widely used for simulating agricultural management effects on crop production and soil and water quality (Ma et al., 2012). The model was applied to simulate the effect of agricultural management practices (irrigation, fertilization, tillage, and crop rotation) on pesticide transport, water use efficiency, water quality, and crop production (Jaynes and Miller, 1999; Saseendran et al., 2007; Malone et al., 2010). Anar et al. (2019) modified the Crop Environment REsource Synthesis (CERES) Beet model and incorporated it into the Cropping System Model (CSM) in DSSAT to simulate growth, development, and yield of sugarbeet. The newly developed CSM-CERES-Beet has also been incorporated into RZWQM2 (version 4.0) for simulating the effects of sugarbeet growth on soil health and water quality (Anar et al., 2017) and tested for sugarbeet growth and production trials at Carrington, North Dakota. However, the newly updated RZWQM2 has not been tested for simulating the effects on sugarbeet growth of different crop rotation and tillage operation scenarios. Therefore, the objective of the current research is two-fold: (1) to test RZWQM2's capability of modeling crop rotation and tillage involved in sugarbeet production, and (2) to simulate the effects of crop rotation and tillage on sugarbeet yield and soil nitrate to gain a better understanding of the environmental impacts of sugarbeet-based biofuel production in the RRV region. Although the RRV region has its distinctive features, the lessons learned from this research can be extended to other regions in the U.S. and around the world.

Materials and Methods

Field Experiment

Site Description and Data Collection

A field experiment was conducted at the Carrington Research Extension Center, Carrington, North Dakota (47.510°

N, 99.123° W). Soils in the experimental plots were loam with an average pH of 6.8. Soil profile characteristics of the study site are listed in table 1. The climate of the study area is typically continental with cold winters and hot summers, with an average annual temperature of 4.3°C and precipitation of 477 mm. The highest monthly average precipitation (84 mm) is observed in June, and the highest monthly average temperature (26.6°C) is observed in July. The weather inputs required to run RZWQM2 were collected from a North Dakota Agricultural Weather Network (NDAWN) station at Carrington (47.509° N, 99.132° W, elevation of 476 m). Weather data for 1990 to 2017 were collected and used for long-term simulation.

The experimental site consisted of 48 plots, each 15.24 m × 12.2 m (50 ft × 40 ft) size. Sugarbeet was cultivated in rotation with corn, soybean, and wheat. The cultivars of sugarbeet, corn, and wheat used for the crop rotation experiments were X401, DKC33-78RIB, and Prosper, respectively. For soybean, Dairyland 0404 was used in the first two years, and Proseed 3020 was used in the third year. The planting date, harvest date, planting density, and fertilization rate for each crop are given in table 2. Fertilizers were broadcasted on the surface one day before planting. All crops were rainfed.

Because sugarbeet was the crop of concern, we collected detailed data on leaf, stem, and root periodically from four and eight times during the growing season over the three-year study period for top and root weight measurements. Leaf area index (LAI) was measured using the ground-based measurement method based on radiative transfer theory (Hemayati and Shirzadi, 2011). For the other crops, only final yield data were recorded at harvest. Soil water content (SWC) and soil nitrate concentration data were also collected from several different sugarbeet plots. Soil water contents at four different soil depths (0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm) were measured using *in situ* neutron probes (Troxler Electronic Laboratories, Durham, N.C.). Soil samples were also analyzed periodically by Agvise Laboratories (Northwood, N.D.) for soil profile nitrate concentrations in the soil layers. SWC was measured on eight different dates between June 16 and September 28, 2016, while soil nitrate samples were collected on seven different dates between June 30 and October 4, 2016. Details on the field experiment and data collection were provided by Anar et al. (2017).

Table 1. Average characteristics of the soil profiles at the Carrington Research Extension Center.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil Type	OM (%)	EC (mmhos cm^{-1})
0-15	45	34	21	Loam	4.0	0.16
15-30	47	36	17	Loam	3.6	0.25
30-45	49	28	23	Loam	-	-
45-60	53	28	19	Sandy loam	-	-
60-120	65	25	10	Sandy loam	-	-

Crop Rotations and Tillage Operations

The four crop rotation sequences from the field experiment were used for model calibration and evaluation. As shown in table 3, sugarbeet followed wheat or sugarbeet, corn followed only sugarbeet, wheat followed soybean or corn, and soybean followed only corn as the previous crops in the field experiment. Because no corn was grown in 2014 in these four crop rotations, we used a different set of crop yields within the same study site for corn in 2014 to calibrate the crop cultivar parameters of CSM-CERES-Maize (table 4).

The effects of conventional tillage (CT) and no-tillage (NT) were compared only in the sugarbeet plots. Each sugarbeet plot was equally divided into two halves, with CT performed in one half of the plot by disking to a depth of 7.5 cm and NT in the other half. Tillage was performed in the fall of the previous year. Before planting, a field cultivator was used for land preparation to a depth of 5 cm.

Model Calibration

Crop cultivar parameters were calibrated for the specific crop models available in RZWQM2 v4.0: CSM-CERES-Maize for corn, CROPSIM-Wheat for wheat, CROPGRO-Soybean for soybeans, and CSM-CERES-Beet for sugarbeet. Only grain yields at harvest were measured for corn,

Table 3. Four crop rotation sequences in field experiment.

Sequence	First-Year Crop (2014)	Second-Year Crop (2015)	Third-Year Crop (2016)
A	Soybean	Wheat	Sugarbeet
B	Sugarbeet	Corn	Soybean
C	Wheat	Sugarbeet	Corn
D	Sugarbeet	Sugarbeet	Sugarbeet

Table 2. Crop management details for field experiment.

Crop	Management	2014	2015	2016
Corn	Planting date	May 23	May 23	May 9
	Harvest date	November 3	November 3	October 24
	Planting density	98,800 seeds ha^{-1}	98,800 seeds ha^{-1}	98,800 seeds ha^{-1}
	Fertilization (kg ha^{-1})	N: 201, P: 22.42, S: 11.21	N: 201, P: 22.42, S: 11.21	N: 201, P: 22.42, S: 11.21
Soybean	Planting date	June 2	June 4	May 19
	Harvest date	October 10	October 10	October 10
	Planting density	494,000 seeds ha^{-1}	494,000 seeds ha^{-1}	494,000 seeds ha^{-1}
	Fertilization	None	None	None
Sugarbeet	Planting date	May 27	June 1	May 12
	Harvest date	October 17	October 17	October 11
	Planting density	121,030 seeds ha^{-1}	121,030 seeds ha^{-1}	121,030 seeds ha^{-1}
	Final stand	74,000 seeds ha^{-1}	118,560 seeds ha^{-1}	Varied seeds ha^{-1}
	Fertilization (kg ha^{-1})	N: 112, P: 22.42, S: 11.21	N: 112, P: 22.42, S: 11.21	N: 112, P: 22.42, S: 11.21
Wheat	Planting date	May 23	May 23	May 13
	Harvest date	September 3	September 3	August 26
	Planting density	2.9 million seeds ha^{-1}	2.9 million seeds ha^{-1}	2.9 million seeds ha^{-1}
	Fertilization (kg ha^{-1})	N: 168, P: 22.42, S: 11.21	N: 168, P: 22.42, S: 11.21	N: 168, P: 22.42, S: 11.21

wheat, and soybean in 2014-2016. The crop parameters for these crops were manually calibrated based on observed grain yields in 2014 and are listed in tables 4 to 6. Although two varieties of soybean were planted during the study period, only one set of parameters was used. For sugarbeet, PEST was used to calibrate the cultivar parameters of CSM-CERES-Beet against field observations of LAI, top weight, and root weight throughout the growing season (Anar et al., 2017, 2019), and the calibrated cultivar parameters for sugarbeet are also listed in table 7. Initial soil conditions were set based on the initial soil conditions in 2014 and were kept the same for all crop parameter calibrations. Once the model was calibrated, the soil conditions were evaluated for the following two years in a sequential run (2015 and 2016) in all four crop rotation sequences.

The parameter values for soil bulk density and saturated hydraulic conductivity for different soil layers, to 120 cm depth, were directly adopted from Anar et al. (2017). Because we did not have measurements of soil water content at 1/3 bar suction head ($\theta_{1/3}$) or 15 bar suction head (θ_{15}), the Brooks-Corey (BC) parameters were estimated based on soil texture classes according to Rawls et al. (1982) in the RZWQM2 model (Fang et al., 2010; Ma et al., 2012) (table 8). Except for residual water content (θ_r), other BC

Table 4. Cultivar parameter values for corn (variety: DKC33-78RIB).

Parameter	Definition	Calibrated Value
P1	Thermal time from seedling emergence to the end of the juvenile phase (°C-days)	120
P2	Delay in development for each hour that daylength is above 12.5 h (days h^{-1})	0.40
P5	Thermal time from silking to physiologic maturity (°C-days)	860
G2	Maximum possible number of kernels	850
G3	Kernel filling rate (mg d^{-1})	18
PHINT	Phyllochorn interval in thermal time between successive leaf tip appearance (°C-days)	34

Table 5. Cultivar parameter values for wheat (variety: Prosper).

Parameter	Definition	Calibrated Value
P1V	Days at the optimal vernalizing temperature required to complete vernalization (days)	28
P1D	Percent reduction in development when photoperiod in 10 h less than the threshold (P1DT = 20 h)	75
P5	Grain filling duration phase (°C-days)	500
G1	Kernel number per unit canopy weight at anthesis (g^{-1})	35
G2	Standard kernel size under optimum condition (mg)	60
G3	Standard non-stressed dry weight of a single tiller at maturity (g)	4
PHINT	Phyllochorn interval in thermal time between successive leaf tip appearance (°C-days)	60

Table 6. Cultivar parameter values for soybean (variety: Dairyland 0404).

Parameter	Definition	Calibrated Value
CSDL	Critical short-day length below which reproductive development progresses with no day length effect (h)	14.84
PPSEN	Slope of relative response of development to photoperiod with time (h^{-1})	0.10
EM-FL	Time between plant emergence to flower appearance (°C-days)	18
FL-SH	Time between first flower and first pod (°C-days)	10
FL-SD	Time between first flower and first seed (°C-days)	15
SD-PM	Time between first seed and physiologic maturity (°C-days)	37.59
FL-LF	Time between first flower and end of leaf expansion (°C-days)	17
LFMAX	Maximum leaf photosynthesis rate at 30°C (CO_2 m^{-2} s^{-1})	2.60
SLAVR	Specific leaf area of cultivar under standard growth condition (cm^2 g^{-1})	280
SIZLF	Maximum size of full leaf (cm^2)	180
XFRT	Maximum fraction of daily growth that is partitioned to seed and shell	1
WTPSD	Maximum weight per seed (g)	0.19
SFDUR	Seed filling duration for pod cohort at standard growth conditions (°C-days)	23
SDPDV	Average seed per pod under standard condition (pod^{-1})	2.20
PODUR	Time required for cultivar to reach final pod load under optimal conditions (°C-days)	8

Table 7. Cultivar parameter values for sugarbeet (Variety: X401).

Parameter	Definition	Calibrated Value
P1	Thermal time from seedling emergence to the end of juvenile phase (°C-days)	940
P2	Photoperiod sensitivity (h^{-1})	0.001
P5	Thermal time from panicle initiation to physiological maturity (°C-days)	700
G2	Leaf expansion rate during leaf growth stage (cm^2 cm^{-2} d^{-1})	220
G3	Maximum root growth rate (g m^{-2} d^{-1})	37.5
PHINT	Phyllochorn interval in thermal time between successive leaf tip appearance (°C-days)	43

Table 8. Brooks-Corey parameters used in model simulations.

Horizon Depth (cm)	Bulk Density (ρ_b, g cm^{-3})	Saturated Hydraulic Conductivity (K_{sat}, cm h^{-1})	Saturated Water Content (θ_s, cm^3 cm^{-3})	Residual Water Content (θ_r, cm^3 cm^{-3})	Bubbling Pressure (ψ_b, cm)	Particle Size Distribution Index (λ)	1/3 bar Water Content ($\theta_{1/3}$, cm^3 cm^{-3})	15 bar Water Content (θ_{15}, cm^3 cm^{-3})
15	1.438	1.18	0.413	0.027	2.17	0.217	0.156	0.083
30	1.091	1.04	0.554	0.027	0.485	0.151	0.223	0.111
60	1.106	3.00	0.548	0.027	0.517	0.137	0.242	0.120
90	1.000	3.00	0.622	0.041	0.275	0.166	0.219	0.093
120	1.873	3.00	0.293	0.041	2.736	0.463	0.068	0.048

parameters (θ_s, ψ_b, and λ) were adjusted based on bulk density (ρ_b) by the model according to the relationships defined among the BC parameters (Ahuja et al., 2000; Ma et al., 2012). Residual water content (θ_r) was obtained from Rawls et al. (1982) for each soil texture class. The water content at any suction head (e.g., $\theta_{1/3}$, θ_{15}) could also be computed from these BC parameters. Table 8 lists the parameter values for soil hydraulic properties at different soil depths when the model was calibrated.

MODEL EVALUATION

For evaluation of the model performance, we calculated both the relative root mean square error (rRMSE) and the index of agreement (d) as indicators of goodness-of-fit. The rRMSE is the root mean square error normalized to the mean of the observed values:

$$\text{rRMSE} = \frac{\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(y_i - y_i'\right)^2}}{\left|\bar{y}\right|} \quad (1)$$

where m is the number of observations, $\bar{y}$ is the mean of the observed values, y_i' is the model-simulated value, and y_i is the observed value. Moriasi et al. (2007) suggested that rRMSE ≤ 0.70 is considered acceptable for model performance. The index of agreement is estimated using the following equation:

$$\text{d} = 1 - \frac{\sum_{i=1}^{m}\left(y_i - y_i'\right)^2}{\sum_{i=1}^{m}\left(\left|y_i' - \bar{y}\right| + \left|y_i - \bar{y}\right|\right)^2} \quad (2)$$

The index of agreement is more sensitive than traditional correlation measures to differences between observed and simulated means and variances. The d-value varies between 0 and 1, with higher values indicating better fit (Legates and McCabe, 1999).

LONG-TERM CROP ROTATION AND TILLAGE SCENARIOS

Long-term crop rotation and tillage scenarios were designed to simulate their effects on sugarbeet yield and soil nitrate. The five rotation scenarios were: (1) corn-sugarbeet-wheat-sugarbeet, (2) wheat-sugarbeet-corn-sugarbeet, (3) soybean-sugarbeet-wheat-sugarbeet, (4) wheat-sugarbeet-soybean-sugarbeet, and (5) continuous sugarbeet. Each scenario was run for 28 years (from 1990 to 2017) to simulate the long-term effects of prior crops on sugarbeet yield and soil nitrate. The same planting date, planting density, planting depth, row width, and fertilization rate were used for all years and all rotation sequences (table 9). No tillage was applied during these long-term crop rotation simulations.

Separately, we also simulated the effects of four tillage operations on sugarbeet yield and soil nitrate: moldboard plow (MP, to a depth of 15 cm), chisel plow (CP, to a depth of 13 cm), field cultivator (FC, to a depth of 10 cm), and no-tillage (NT). Tillage operations were implemented only on the continuous sugarbeet plots for the same 28 years from 1990 to 2017. Crop management practices for sugarbeet were the same under these tillage operations as described in table 9. In RZWQM2, tillage affects soil bulk density and soil hydraulic properties (Ahuja et al., 1998), as well as residue incorporation and macropore connectiveness (Ahuja et al., 2000).

RESULTS AND DISCUSSION

MODEL CALIBRATION AND EVALUATION

Crop Yields

Figure 1 shows comparisons of the observed and simulated crop yields for the four crop rotation sequences in 2014-2016. Overall, the model performed well in simulating crop yields for all four crops in the four crop rotations. Table 10 shows that all rRMSE values for crop yield were less than 0.25, and all d-values were greater than 0.95. However, the yields of all the crops (i.e., sugarbeet, corn, and wheat) planted in 2016, the last year of the rotation sequences, were overestimated by 14.61% to 112.7%. A close inspection of figure 1 reveals that the observed crop yields in 2016 were generally lower than those in the previous years. For example, the average wheat yield was 4006 and 3458 kg ha^{-1} in 2014 and 2015, respectively, but only 1724 kg ha^{-1} in 2016, The observed yields of corn and sugarbeet were also lower in 2016. No soybeans were planted in 2016 in any of the four sequences.

A possible reason for the lower observed sugarbeet yield in 2016 was poor plant establishment (i.e., 46,574 plants ha^{-1} in continuous sugarbeet rotation; fig. 1d) as compared to 2014 (74,000 plants ha^{-1}) and 2015 (118,560 plants ha^{-1}), which may also be true for the other crops. For model simulation, we used the average plant densities for all the plots. Figure 1a shows that the field observed sugarbeet yields were lower than the model-simulated yields, with high standard errors. Variable plant stands in the observations versus average plant stands in the model input may also have had an impact on the yield difference. For other crops, we had to use the initial planting density as model input because the final stands for wheat, corn, and soybean were not available. However, in our field visits, weeds were visible in 2016, which may have caused lower final stands for those crops and resulted in lower field yields compared to the model-simulated yields.

Soil Water and Nitrate

The observed and simulated soil water contents in the sugarbeet plots for sequence A (sugarbeet following wheat)

Table 9. Crop management practices to simulate long-term crop rotation and tillage effects.

Management	Corn	Soybean	Sugarbeet	Wheat
Planting date	May 23	June 2	May 27	May 23
Harvest date	November 3	October 10	October 17	September 3
Planting density	98,800 seeds ha^{-1}	494,000 seeds ha^{-1}	74,000 seeds ha^{-1}	2.9 million seeds ha^{-1}
Fertilization	N: 201 kg ha^{-1}	N: 50 kg ha^{-1}	N: 112 kg ha^{-1}	N: 168 kg ha^{-1}

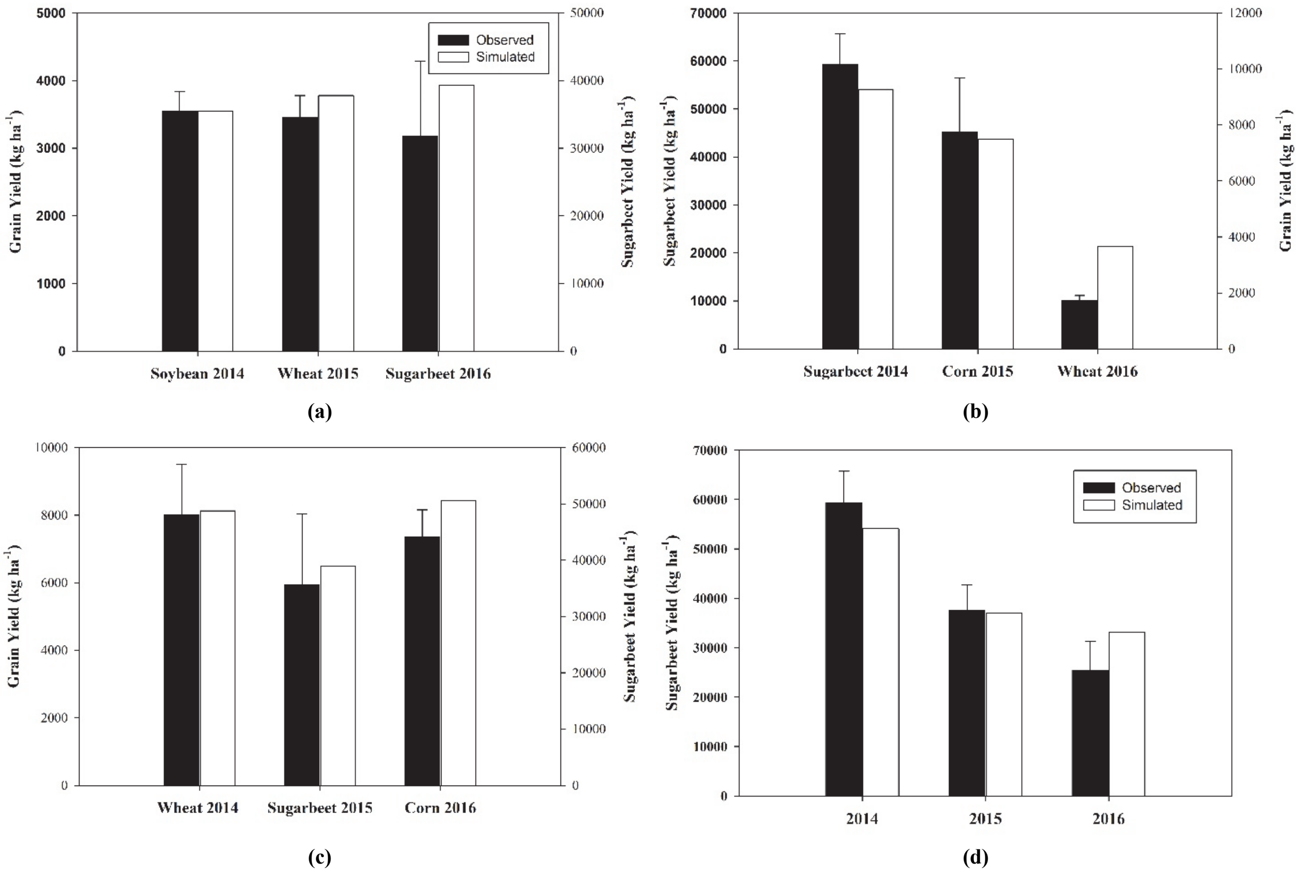

Figure 1. Comparisons of observed and model-simulated crop yields for different crop rotation sequences: (a) soybean-wheat-sugarbeet (sequence A), (b) sugarbeet-corn-soybean (sequence B), (c) wheat-sugarbeet-corn (sequence C), and (d) continuous beet (sequence D) in 2014 (model calibration) and in 2015 and 2016 (model evaluation).

Table 10. Statistics of model performance for crop yields, soil water, and soil nitrate.

Observations and Crop Rotation Sequence[a]	Soil Layer (cm)	Number of Observations	rRMSE	Index of Agreement (d)
Yield (2014-2016)				
A	-	3	0.242	0.982
B	-	3	0.147	0.997
C	-	3	0.118	0.997
D	-	3	0.100	0.949
Soil water (2016)				
A	0-1	8	0.224	0.709
	15-30	8	0.229	0.722
	30-45	8	0.135	0.877
	45-60	8	0.195	0.541
D	0-15	8	0.070	0.676
	15-30	8	0.099	0.564
	30-45	8	0.055	0.704
	45-60	8	0.083	0.668
Soil nitrate (2016)				
A	0-15	7	2.773	0.654
	15-30	7	0.990	0.765
	30-45	7	1.110	0.652
	45-60	7	1.392	0.500
D	0-15	7	0.662	0.873
	15-30	7	0.242	0.982
	30-45	7	1.35	0.616
	45-60	7	1.605	0.610

[a] A = soybean-wheat-sugarbeet, B = sugarbeet-corn-soybean, C = wheat-sugarbeet-corn, and D = continuous sugarbeet.

and sequence D (continuous sugarbeet) are presented in figure 2, as sugarbeet was our crop of concern, while the observed and simulated soil nitrate in the sugarbeet plots for sequences A and D are presented in figure 3. The 1:1 diagonal lines represent perfect matching between the observed and simulated values. The model evaluation statistics (rRMSE and d-values) are listed in table 10. As shown in figures 2 and 3, the simulated soil water and soil nitrate in the sugarbeet plots for both sequences matched reasonably well with the measured values, and the model simulation was better for soil water than for soil nitrate. The rRMSE values ranged between 0.055 and 0.229 for soil water and between 0.242 and 2.773 for soil nitrate, with d-values ranging between 0.541 and 0.877 for soil water and between 0.500 and 0.982 for soil nitrate (table 10).

Errors in simulating soil water and nitrate with RZWQM2 may be introduced by the lack of site-specific bulk density and saturated hydraulic conductivity (K_{sat}) values in the model when there may be considerable spatial heterogeneity in the soil properties across the field (Ma et al., 2007a; Saseendran et al., 2007). Simulation errors in daily soil nitrate concentrations could also be caused by the difficulties in modeling different soil organic and microbial pools and the extent to which these errors propagate into the daily mineralization of organic matter, which is mainly governed by microbial processes (Saseendran et al., 2007).

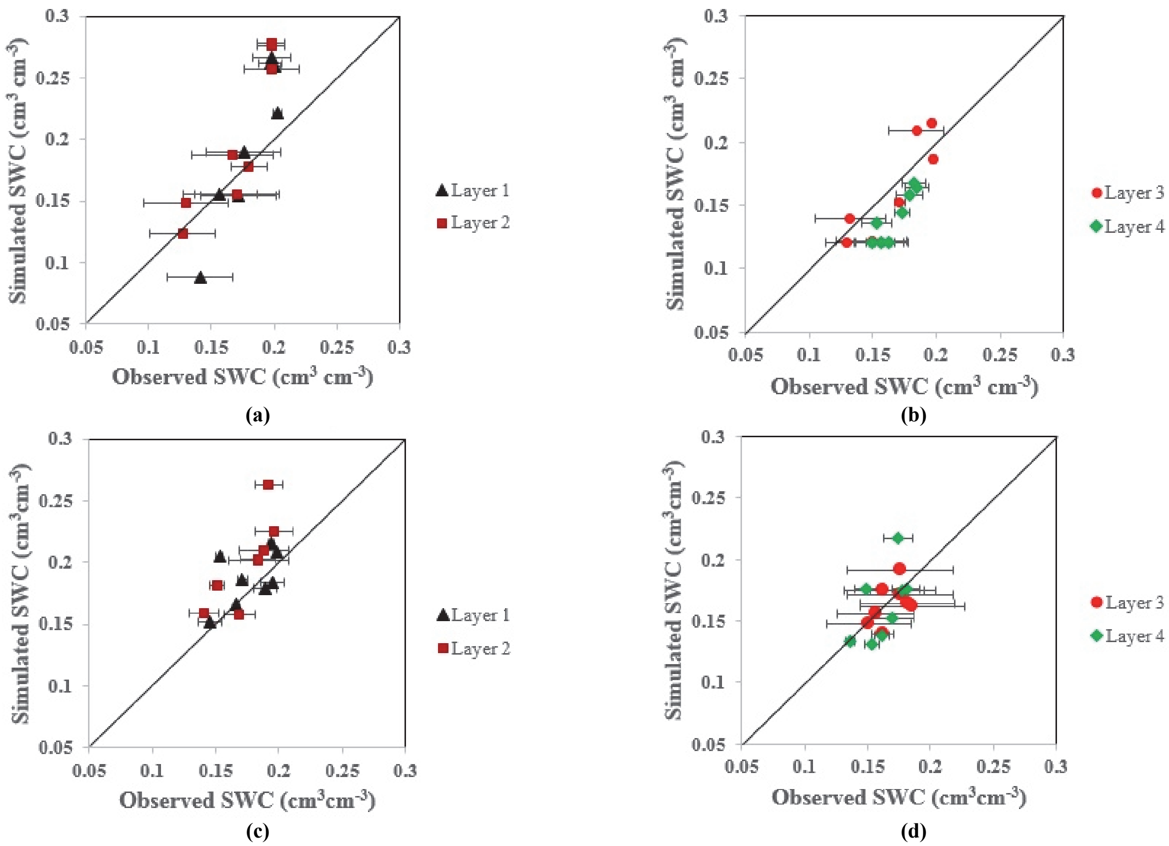

Figure 2. Soil water content (SWC) in sugarbeet plots in 2016: (a) layer 1 (0-15 cm) and layer 2 (15-30 cm) and (b) layer 3 (30-45 cm) and layer 4 (45-60 cm) in sequence A (following wheat), and (c) layer 1 (0-15 cm) and layer 2 (15-30 cm) and (d) layer 3 (30-45 cm) and layer 4 (45-60 cm) in sequence D (following sugarbeet). Horizontal bars and whiskers represent standard errors for observed soil water contents in sugarbeet plots. Diagonal lines are 1:1 reference lines.

Tillage

The newly developed sugarbeet model, CSM-CERES-Beet, was also evaluated for the effect of tillage operations (NT and CT) on sugarbeet yields in 2015 and 2016. As shown in figure 4, the model adequately simulated sugarbeet yields for both tillage scenarios, except that the model over-predicted the sugarbeet yield in 2015 for NT. Figure 4 also shows that CT operations produced higher sugarbeet yields compared to NT operations in both 2015 and 2016. Tillage may have affected the final sugarbeet plant population in the field, but RZWQM2 did not simulate tillage effects on plant establishment. The final average sugarbeet plant population was approximately 46,574 and 15,675 plants ha^{-1} in the CT and NT fields, respectively. Unfortunately, the final sugar-beet stands for tillage and no-tillage operations were not recorded in 2015. A higher weed infestation was also observed in the fields in 2016, which was not simulated by the model.

Long-Term Effects of Crop Rotation on Sugarbeet Yield and Soil Nitrate

Figure 5 shows the simulated sugarbeet yields following different crops in the five long-term crop rotation scenarios. The average sugarbeet yields over the 28 years (1990-2017) are also plotted as boxplots in figure 6 to compare the overall effects of the four previous crops on sugarbeet yield. Figure 6 shows that sugarbeet had the highest yield when the previous crop was wheat, while it had the lowest yield when it followed soybean. The effect of prior corn on sugarbeet yield was between wheat and soybean. Analysis of variance of the data showed that the effect of previous-year crops on sugar-beet yield was not statistically significant ($p = 0.6054$). Tukey multiple comparisons also suggested that the differences between all the pairs were not statistically significant (table 11). On average, sugarbeet yield was 57,952 kg ha^{-1} in continuous beet, 62,040 kg ha^{-1} when following wheat, 59,971 kg ha^{-1} when following corn, and 58,024 kg ha^{-1} when following soybean. Overstreet et al. (2007) and Sims (2009) observed greater sugarbeet yields when sugarbeet followed wheat compared to following corn or soybean due to slightly higher moisture content and N availability, which was corroborated by our model simulations (figs. 2 and 3). In their studies, Sims (2009) and Overstreet et al. (2007) also observed lower sugarbeet yield when sugarbeet followed corn, and slightly higher yield when it followed soybean. However, in our model simulations, sugarbeet had higher yields after corn compared to after soybean.

Figure 7 compares the soil profile nitrate in the top 60 cm in sugarbeet plots following four different prior crops. It suggests that soil nitrate content dynamics in the sugarbeet plots were very similar throughout the entire growing season following corn, wheat, soybean, or continuous sugarbeet (figs. 7a to 7d), with slightly higher nitrate content following soybean during 0 to approximately 40 days after planting in the top two layers (figs. 7a and 7b). Sims (2009) also observed higher nitrate in the first two layers when sugarbeet followed soybean in the crop rotation.

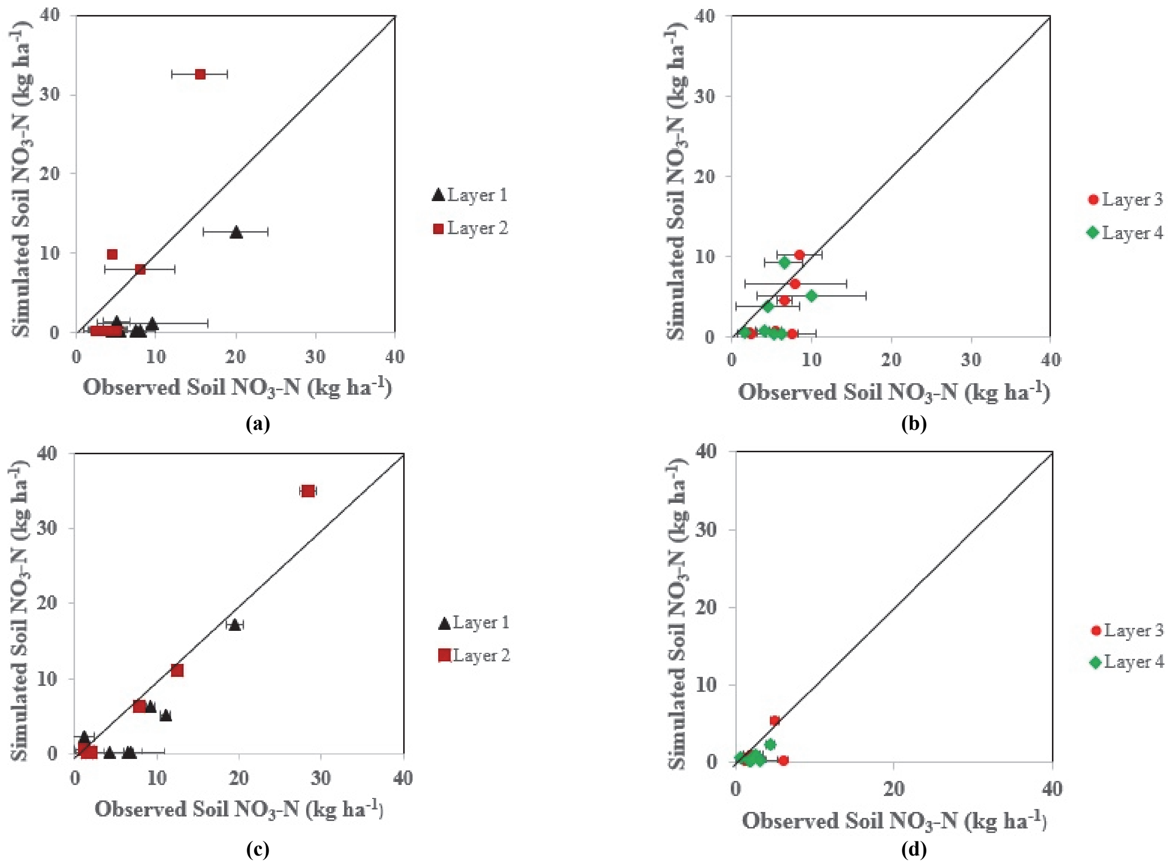

Figure 3. Soil nitrate content in sugarbeet plots in 2016: (a) layer 1 (0-15 cm) and layer 2 (15-30 cm) and (b) layer 3 (30-45 cm) and layer 4 (45-60 cm) in sequence A (following wheat), and (c) layer 1 (0-15 cm) and layer 2 (15-30 cm) and (d) layer 3 (30-45 cm) and layer 4 (45-60 cm) in sequence D (following sugarbeet). Horizontal bars and whiskers represent the standard errors for observed soil water contents in sugarbeet plots. Diagonal lines are 1:1 reference lines.

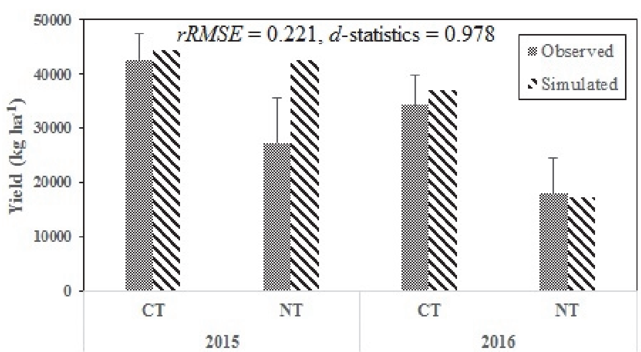

Figure 4. Comparison of observed and simulated sugarbeet yields with conventional tillage (CT) and no-tillage (NT).

Table 12 shows the average N mass balance simulated for the 1990-2017 cropping seasons, with the N uptake and net mineralization rates ranging between 151 and 153 kg ha^{-1} and between 55 and 57 kg ha^{-1}, respectively, for the different crop rotations. In their long-term crop production simulation study using RZWQM2, Ma et al. (2007b) observed 67 to 223 kg ha^{-1} N mineralization for corn-soybean crop production systems. In this simulation, the higher N uptake and net mineralization were from the sugarbeet fields following wheat (table 12). In contrast, when sugarbeet followed sugarbeet, the N uptake and mineralization were lowest. The seasonal N mass balance in table 12 also showed lower average N stresses following wheat compared to the other crops. The soil water mass balance (table 13) showed slightly lower actual transpiration and evaporation, indicating lower average water stress and higher water availability following wheat. Sims (2007) also observed lower N mineralization in sugarbeet fields when following corn compared to when following soybean or wheat, with a small difference between wheat and soybean. Lamb et al. (2001) indicated that the N credit after soybeans was substantiated by studies that were mostly based on growing corn after either soybean or corn.

A closer inspection of figure 5 reveals that, in 2011, sugarbeet yields were more than 30% higher following wheat compared to those following corn or soybean. In 2011, the N uptake by sugarbeet was 167.2 kg ha^{-1} and the N mineralization rate was 67.3 kg ha^{-1} when sugarbeet followed wheat. However, the N uptake rate by sugarbeet following corn or soybean was approximately 150 kg ha^{-1}, the N mineralization rate was around 56 kg ha^{-1}, and both were considerably smaller than that following wheat.

The simulated N losses to runoff in the sugarbeet fields during the 1990-2017 cropping seasons with different previous crops were identical at 0.74 kg ha^{-1}. The N losses to drainage (i.e., N leaching out of the bottom of the soil profile) in the fields of sugarbeet following four different prior crops were between 0.52 and 0.62 kg ha^{-1}, which indicates that the difference in the effect of crop rotation on the environment is negligible.

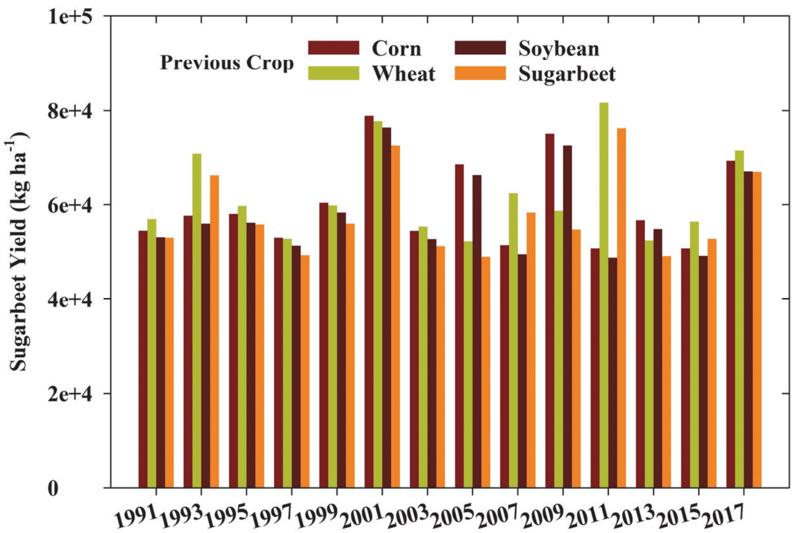

Figure 5. Sugarbeet yields following different crops (corn, wheat, soybean, and sugarbeet) in five long-term crop rotation scenarios.

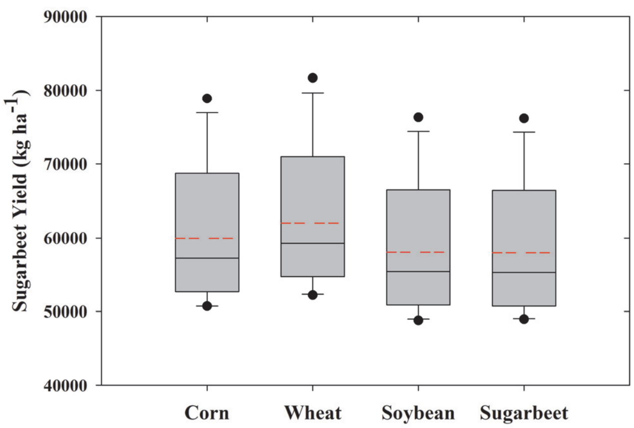

Figure 6. Effects of previous crops in crop rotation on sugarbeet yields.

Table 11. Results of Tukey HSD test for effects of long-term crop rotations on sugarbeet yield.

Treatment Pair	Q Statistic	p-Value	Inference
Corn vs. Wheat	0.8415	0.8999947	Insignificant
Corn vs. Soybean	0.7914	0.8999947	Insignificant
Corn vs. Sugarbeet	0.8206	0.8999947	Insignificant
Wheat vs. Soybean	1.6329	0.6404855	Insignificant
Wheat vs. Sugarbeet	1.6620	0.6290565	Insignificant
Soybean vs. Sugarbeet	0.0292	0.8999947	Insignificant

Long-Term Effects of Tillage on Sugarbeet Yield and Soil Nitrate

The effects of different tillage operations on sugarbeet yields are plotted in figure 8. Although the MP method produced slightly higher yield compared to the other tillage methods, the effects of the tillage operations were not statistically significant ($p = 0.970$). Tukey multiple comparisons suggested statistically non-significant differences between all treatment pairs (table 14). Table 15 further suggests that one of the reasons for the higher sugarbeet yield with MP might be relatively lower average N stresses compared to the other tillage methods. Total evapotranspiration in MP was also slightly lower compared to the other tillage operations (table 16). In their experiment at Sidney, Montana, Tarkalson et al. (2009) tested the effects of different strip tillage methods on sugarbeet production and observed a slightly higher sugarbeet yield with MP compared to CP at a nitrogen fertilization rate of 112 kg ha^{-1}. However, the differences in yield among the different tillage methods in their study were not significant. Non-significant effects of different tillage operation methods on sugarbeet yields were also reported in other research (Hao et al., 2001; Jabro et al., 2010; Tarkalson et al., 2012; Larney et al., 2016).

Nevertheless, the marginal difference observed in the sugarbeet yields with different tillage methods may be due to soil nitrate availability (Campbell et al., 1996; Mitchell et al., 2000; Askegaard et al., 2011). Tillage increases the turnover of soil organic matter, which in turn increases N mineralization and the availability of soil mineral N (Askegaard et al., 2011). Conservation tillage increases water and nutrient holding capacities and ultimately affects soil N availability (Mitchell et al., 2000). No-tillage or strip tillage practices leave most of the crop residue on the undisturbed surface, whereas conservation tillage incorporates residue into the soil and thereby increases soil-residue contact, favoring rapid decomposition of soil organic matter through oxidation (Campbell et al., 1996). A comparison of the model-simulated nitrate content in the top 60 cm is plotted in figure 9. Figures 9a and 9b show that the sugarbeet field that was tilled by MP (up to 15 cm) had the highest nitrate in the upper two layers compared to those tilled by other methods (CP, FC, and NT) during the first 60 days after planting. For the bottom two layers, there was no difference in soil nitrate in the sugarbeet fields among the four tillage methods (figs. 9c and 9d).

Average seasonal N mass balance from the model indicated that tillage affected the nitrate availability in soil N dynamics (table 15). Net mineralization was higher with MP tillage (the deepest tillage) compared to the other methods, indicating that deeper tillage may have affected the soil water and air trafficability. Wright et al. (2005) observed higher mineralization for MP compared to other tillage methods for corn at 0 to 2.5 cm; however, they observed no significant impacts of tillage on mineralizable N from 2.5 to 20 cm.

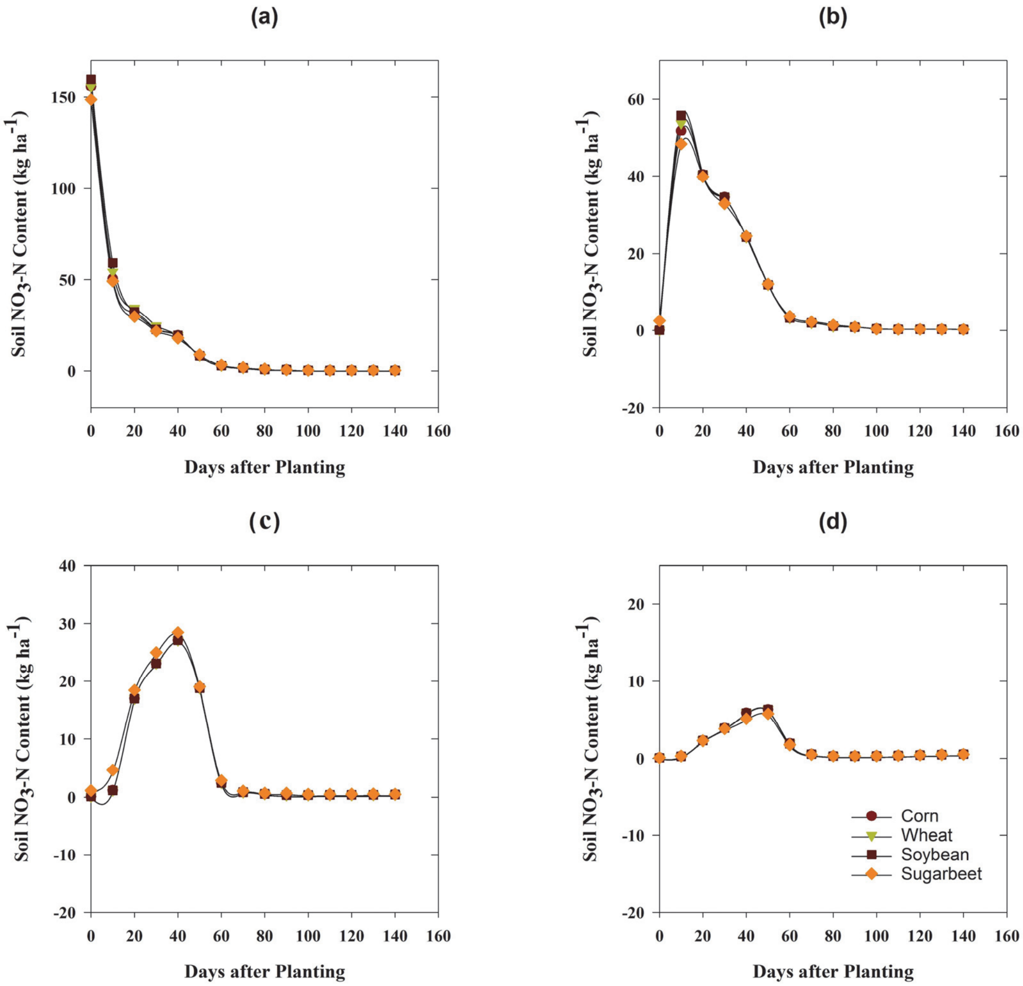

Figure 7. Comparisons of soil nitrate in sugarbeet plots following corn, wheat, soybean, and sugarbeet in (a) 0-15 cm, (b) 15-30 cm, (c) 30-45 cm, and (d) 45-60 cm soil depth layers. Soil nitrate contents are average over simulation years.

Table 12. Simulated soil N dynamics in sugarbeet plots during 1990-2017 with corn, wheat, soybean, and sugarbeet as previous crops.

Previous Crop	N Uptake (kg ha^{-1})	Net Mineralization (kg ha^{-1})	N Fixation (kg ha^{-1})	Denitrification (kg ha^{-1})	N Loss to Runoff (kg ha^{-1})	N Loss to Drainage (kg ha^{-1})	Average N Stress (unitless)
Corn	152.06 ±9.40	57.11 ±5.53	0	2.85 ±1.52	0.74 ±0.48	0.56 ±0.08	0.939 ±0.019
Wheat	153.16 ±9.41	58.96 ±5.44	0	2.86 ±1.52	0.74 ±0.48	0.62 ±0.10	0.936 ±0.016
Soybean	151.93 ±9.39	56.87 ±5.54	96.77 ±32.79	2.87 ±1.52	0.74 ±0.48	0.55 ±0.08	0.939 ±0.020
Sugarbeet	151.39 ±9.27	55.90 ±5.44	0	2.84 ±1.52	0.74 ±0.48	0.52 ±0.07	0.939 ±0.020

Table 13. Simulated soil water dynamics in sugarbeet plots during 1990-2017 with corn, wheat, soybean, and sugarbeet as previous crops.

Previous Crop	Total Actual Evaporation (cm)	Total Potential Evaporation (cm)	Total Actual Transpiration (cm)	Total Potential Transpiration (cm)	Total Infiltration (cm)	Total Runoff (cm)	Average Water Stress (unitless)
Corn	5.14 ±1.48	31.66 ±3.66	26.33 ±4.74	41.64 ±5.28	25.55 ±5.44	5.29 ±3.50	0.807 ±0.080
Wheat	4.89 ±1.37	30.87 ±3.68	26.34 ±4.74	40.96 ±5.08	25.55 ±5.42	5.29 ±3.49	0.806 ±0.079
Soybean	5.16 ±1.48	31.86 ±3.66	26.34 ±4.75	41.68 ±5.28	25.55 ±5.42	5.29 ±3.49	0.808 ±0.080
Sugarbeet	5.16 ±1.48	31.87 ±3.66	26.34 ±4.74	41.63 ±5.28	25.55 ±5.42	5.29 ±3.49	0.807 ±0.080

Seasonal N mass balance also showed greater nitrification and lower denitrification for the deepest tillage operation (table 15) due to improved water and air trafficability. Liu et al. (2005) observed lower nitric oxide (NO) emissions from no-tillage fertilized plots, caused by wetter and less aerated soil conditions that may increase microbial denitrification (Conrad, 1996; McTaggart et al., 2002, Gillette et al., 2017). Soil disturbance from tillage can alter the functional groups of microbial communities, causing differences in denitrification rates (Cavigelli et al., 2012; Gillette et al., 2017).

Table 15 also shows that during the 1990-2017 cropping seasons, the simulated N loss to runoff was lowest (0.18 kg ha^{-1}) in the sugarbeet fields with MP and highest (0.82 kg ha^{-1}) in the sugarbeet fields with no tillage. The difference

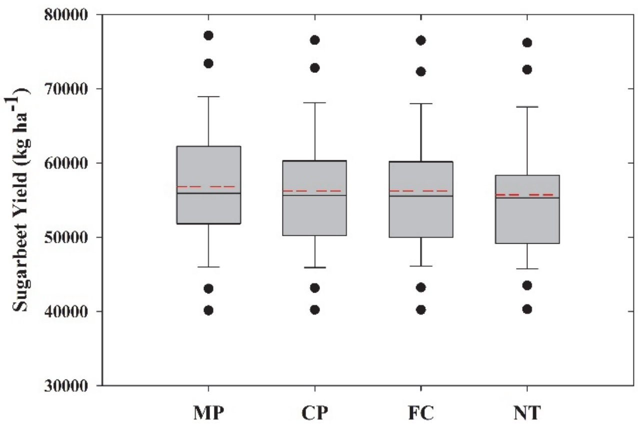

Figure 8. Effects of different tillage operations on sugarbeet yields: MP- = moldboard plow, CP = chisel plow, FC = field cultivator, and NT = no-tillage.

Table 14. Results of Tukey HSD test for effects of long-term tillage operations on sugarbeet yield.

Treatment Pair[a]	Q Statistic	p-Value	Inference
MP vs. CP	0.3452	0.8999947	Insignificant
MP vs. FC	0.3279	0.8999947	Insignificant
MP vs. NT	0.6955	0.8999947	Insignificant
CP vs. NT	0.0173	0.8999947	Insignificant
CP vs. NT	0.3503	0.8999947	Insignificant
FC vs. NT	0.3676	0.8999947	Insignificant

[a] CP = chisel plow, FC = field cultivator, MP = moldboard plow, and NT = no tillage.

in N losses to drainage (i.e., leaching out of the bottom of the soil profile) with different tillage methods was negligible (table 15).

CONCLUSIONS

Sugarbeet as an alternative biofuel source may be gaining importance in the Red River Valley and other regions in the U.S. Both crop rotation and tillage operation may affect soil-available N and thus affect sugarbeet productivity. Sound crop rotation is also the key component of effective pest management and stabilization of sugarbeet yields. For these reasons, modeling the impacts of different crop rotation and tillage scenarios on sugarbeet production is essential for prudent decision-making. In this research, four crop growth models included in RZWQM2 v4.0 (i.e., CSM-CERES-Beet, CSM-CERES-Maize, CROPSIM-Wheat, and CROPGRO-Soybean) were used to assess the impacts of crop rotation and tillage operations on sugarbeet production.

The four crop growth modules in RZWQM2 were first calibrated against field data for 2014 and then evaluated for 2015-2016 using four different crop rotations. The models performed reasonably well in simulating crop yield, soil water, and soil nitrate concentrations (rRMSE = 0.055 to 2.773, d = 0.541 to 0.997). Long-term simulation (1990-2017) showed non-significant effects of crop rotation on sugarbeet yield, although wheat as the previous crop in the rotation resulted in 3% to 6.5% higher sugarbeet yield compared to the other crops due to slightly higher moisture content (lower evapotranspiration) and N availability in the sugarbeet fields following wheat. The effects of tillage operations were also not significant. However, the field tilled with moldboard plow had higher availability of mineralized N compared to chisel plow, field cultivator, and no tillage and resulted in 1% to 2% higher yields.

The main contribution of our study is to demonstrate the ability of RZWQM2 to simulate crop rotation and tillage effects on sugarbeet yield and soil nitrate with reasonable accuracy. To the best of our knowledge, this is the first long-term model simulation study on the effects of crop rotation and tillage on sugarbeet production and environmental quality. There were simulated advantages of growing sugarbeet following wheat and/or with MP tillage, but the effects were not significant, given the errors and uncertainty associated with field experiments and model simulations. When other benefits of crop rotation and tillage, such as weed and disease control, are not considered, crop rotation and tillage had minimal effects on sugarbeet production and negligible effects on N losses to runoff and drainage from the sugarbeet fields.

In the future, the RZWQM2 model may be used for different soil and climatic conditions under different management scenarios in the Red River Valley for longer periods of observed data for better evaluation of the model performance. As sugarbeet production may also be expanded into nontraditional planting areas in the region due to potential demand for biofuel production, RZWQM2 can also be used to assess the associated environmental impacts and suitability of different crop rotation and management scenarios in other areas.

Table 15. Simulated soil N dynamics in sugarbeet plots during 1990-2017 cropping seasons under different tillage operations.

Tillage Operation	N Uptake (kg ha^{-1})	Net Mineralization (kg ha^{-1})	N Fixation (kg ha^{-1})	Denitrification (kg ha^{-1})	N Loss to Runoff (kg ha^{-1})	N Loss to Drainage (kg ha^{-1})	Average N Stress (unitless)
Moldboard plow	151.74 ±7.93	55.11 ±4.93	0	2.61 ±1.01	0.18 ±0.18	0.51 ±0.10	0.934 ±0.022
Chisel plow	151.52 ±7.23	55.16 ±4.48	0	2.23 ±0.81	0.38 ±0.30	0.52 ±0.10	0.937 ±0.023
Field cultivator	151.43 ±7.22	55.17 ±4.46	0	2.31 ±0.86	0.38 ±0.31	0.51 ±0.09	0.937 ±0.023
No tillage	150.09 ±7.20	54.88 ±4.32	0	2.61 ±1.18	0.82 ±0.58	0.52 ±0.09	0.937 ±0.024

Table 16. Simulated soil water dynamics in sugarbeet plots during 1990-2017 cropping seasons under different tillage operations.

Tillage Operation	Total Actual Evaporation (cm)	Total Potential Evaporation (cm)	Total Actual Transpiration (cm)	Total Potential Transpiration (cm)	Total Infiltration (cm)	Total Runoff (cm)	Average Water Stress (unitless)
Moldboard plow	5.06 ±1.24	32.56 ±3.60	26.82 ±4.41	41.62 ±5.02	26.45 ±5.26	3.46 ±2.76	0.807 ±0.079
Chisel plow	5.12 ±1.23	32.73 ±3.67	26.35 ±4.27	41.46 ±4.91	25.90 ±5.13	4.01 ±2.89	0.813 ±0.079
Field cultivator	5.12 ±1.23	32.73 ±3.67	26.34 ±4.27	41.46 ±4.91	25.89 ±5.12	4.02 ±2.89	0.813 ±0.078
No tillage	5.06 ±1.21	32.91 ±3.78	25.88 ±4.22	41.28 ±4.90	25.36 ±5.04	4.55 ±3.04	0.809 ±0.078

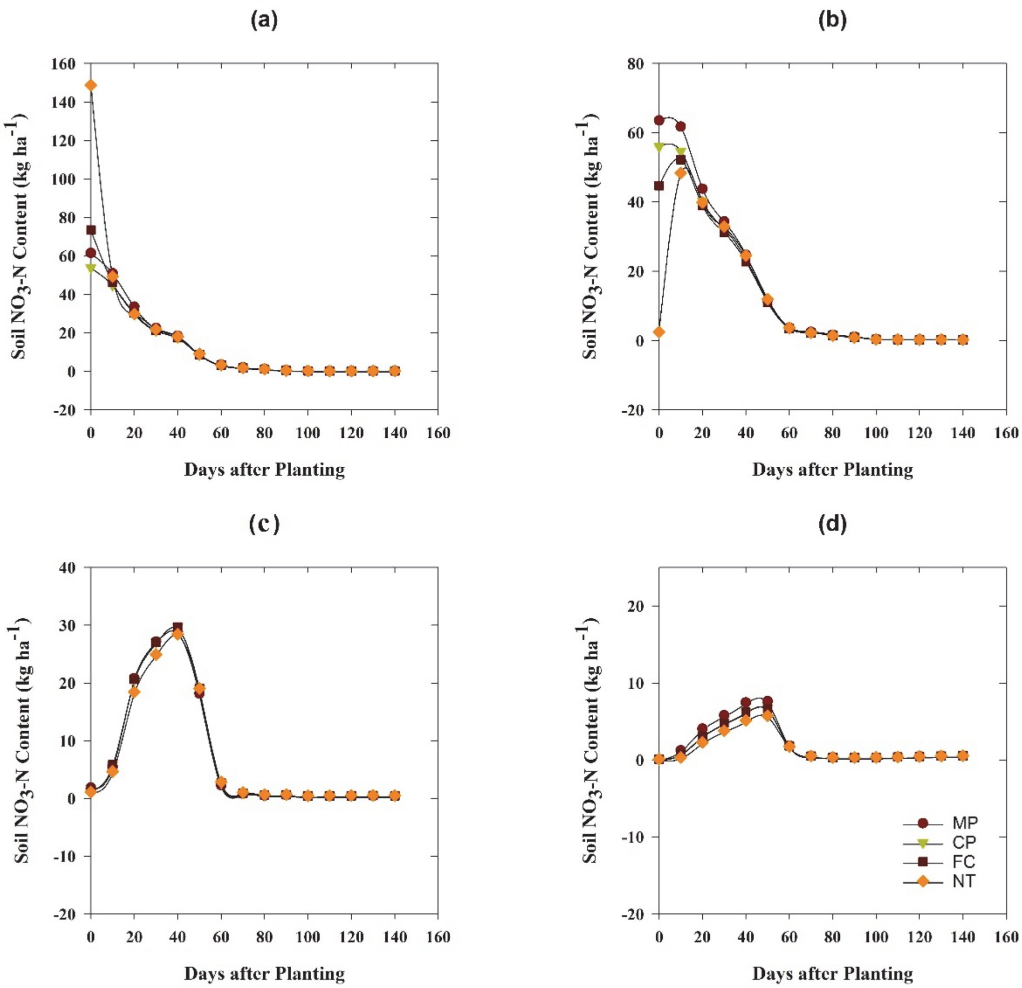

Figure 9. Comparisons of soil nitrate (kg ha^{-1}) in sugarbeet plots under four hypothetical tillage operations in the (a) 0-15 cm, (b) 15-30 cm, (c) 30-45 cm, and (d) 45-60 cm soil depth layers (MP =moldboard plow, CP = chisel plow, FC = field cultivator, and NT = no-tillage). Soil nitrate contents are average over simulation years.

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