ELSEVIER

Soil & Tillage Research 48 (1998) 155–165

Soil & Tillage Research

Tillage system effects on 15-year carbon-based and simulated N budgets in a tile-drained Iowa field

D.L. Karlen[a,*], Ajay Kumar[b], R.S. Kanwar[c], C.A. Cambardella[a], T.S. Colvin[a]

[a] *USDA–Agricultural Research Service, National Soil Tilth Laboratory, 2150 Pammel Dr., Ames, IA 50011, USA*
[b] *Department of Soil and Environmental Sciences, University of California, Riverside, CA 92521, USA*
[c] *Agricultural and Biosystems Engineering Dept., Iowa State University, Ames, IA 50011, USA*

Abstract

Tillage influences N fate and transport by changing soil structure, aeration, macropore continuity, plant-residue placement, and organic-matter mineralization rates. Our objective was to use 15-year N budgets to compare four primary tillage treatments for continuous corn (*Zea mays* L.) production on tile-drained Aquic Hapludolls (FAO: Haplic Phaeozems) in northeastern Iowa, USA. A carbon-based N budget used annual grain yield, grain-N concentrations measured in 1992, changes in surface-soil C content between 1977 and 1988 or 1992, surface-soil C : N ratios, and measurements of NO_3–N lost in tile-drainage water. It accounted for 98, 104, 99, and 99% of the fertilizer N applied to moldboard-, chisel-, ridge-, and no-tillage-treatments, respectively. Averaged for 1977 through 1992, increased soil organic matter, harvested grain, and tile drainage accounted for $\approx$42, 45, and 13% of the N budget, respectively. Simulated N budgets were computed using version 3.25 of the root-zone water quality model (RZWQM). The best grain-yield predictions for 13 of the 15 years were 9% higher than the measured values, and if extreme outliers were eliminated, the predicted values were correlated ($r^2 = 0.75$) with the average measured yield for the four tillage treatments. Simulations for 1988 and 1989 failed completely because RZWQM could not accurately describe hydrology associated with low rainfall seasons. Predicted total N accumulation was much higher than measured in 1990, 1991, or 1992. Estimates of profile NO_3–N, mineralization, seepage loss, and denitrification were not satisfactory, presumably because the model failed to simulate an accurate hydrology for the different tillage practices. We conclude that the simulation results were not suitable for predicting the fate of fertilizer N. However, both approaches for computing N budgets suggested that adopting ridge tillage, without changing N rates and other management practices related to N application technology and crop sequencing, will not reduce the potential for off-site water quality degradation.

Keywords: RZWQM; Simulation modeling; C : N ratios; Nitrate; Carbon; *Zea mays* L.

1. Introduction

Agricultural production practices throughout the world are ecologically leaky with respect to N. This not only results in N losses which reduce the economic efficiency of crop production, but also increases the potential for contamination of surface and groundwater resources (Power and Schepers, 1989; Fletcher, 1991). The potential for N loss is even greater if the soils require subsurface tile drainage for optimum crop production (Gast et al., 1978). From an economic

---

[*] Corresponding author. Tel.: +1 515 294 3336; fax: +1 515 294 8125; e-mail: DKarlen@NSTL.Gov

0167-1987/98/$ – see front matter
PII: S0167-1987(98)00142-1

perspective, however, the lack of artificial drainage may cause more immediate and measurable losses to persons managing some agricultural soils. These losses occur because of poor growing conditions that result in crop damage, with reduced yields in moderately wet years or total crop failure in very wet years (Kanwar et al., 1983; Ahmad et al., 1992).

Several soil and crop management practices can be used to reduce potential negative environmental effects of agriculture while sustaining production and improving economic viability for producers. This includes changing tillage practices or crop sequences, accounting for residual organic and inorganic N pools through soil and plant analysis, and using more precise fertilizer N placement, timing, and rates of application. Each of these practices will have an effect, but quantifying and integrating these effects remains a major challenge throughout the U.S. and around the world.

One method for assessing the environmental, production, and economic effects of different management practices is to use long-term research data to compute nutrient budgets. Simple assessments for N can be made by accounting for inputs, crop removal, loss through tile drainage, and changes in soil N. Assessments can also be made by using simulation models, such as the root-zone water quality model (RZWQM) (USDA–ARS, 1995) or the nitrate-leaching and economic analysis package (NLEAP) (Shaffer et al., 1991).

Simulation models can be effective scientific tools for evaluating the impact of agricultural management practices on soil and water quality, provided they are reasonably calibrated for the soil, climate, and crop conditions for which they are used. The RZWQM is designed for assessing the environmental impact of alternative agricultural management strategies on a field-by-field basis, but it is important to recognize that RZWQM was not developed for rigorous quantitative predictions (USDA–ARS, 1995).

Our objective was to use a simple carbon-based N budget and the RZWQM to assess the fate of N fertilizer applied to continuous corn grown using ridge tillage, moldboard plowing, chisel plowing, or no tillage as the primary practices for seedbed preparation. This report is not intended to be a rigorous evaluation of the RZWQM because the field-based parameters used for the N budget also have substantial uncertainty. Despite the limitations, the approaches should be applicable for any location where data needed for a precise N budget have not been collected.

2. Methods and materials

2.1. Site characteristics

Our field experiment was established on a 15-ha site near Nashua, IA, in 1977, and managed without changing tillage, N fertilization, or herbicide management practices through 1992. The entire study had 36 plots, each of 0.4 ha area, involving continuous corn and both phases of a two-year corn and soybean [*Glycine max* (L.) Merr.] rotation. The predominant soils within the field site were Floyd loam (fine loamy, mixed, mesic Aquic Hapludolls), Kenyon loam (fine-loamy, mixed, mesic Typic Hapludolls), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls). All three soils are classified as 'Haplic Phaeozems' using FAO nomenclature. These silty soils developed from loamy glacial till, are moderately-well-to-poorly-drained, have a seasonally high water table located from 0.6 to 1.2 m below the soil surface, and generally have 24–30 (g C) kg^{-1} (42–52 (g organic matter) kg^{-1}) in the surface horizons (USDA–NRCS, 1995).

2.2. Tillage treatments

Primary tillage treatments included ridge tillage, moldboard plowing, chisel plowing, or no tillage for seedbed preparation. The moldboard-plow plots were plowed in the fall to a depth of 15–20 cm and then disked in the spring to a depth of ca. 10 cm. Chisel-plow plots were chiseled at a depth of 15–18 cm in the fall and smoothed with a field cultivator which tilled the upper 5–8 cm of soil in the spring. The ridge-tillage plots had the top of the ridge removed by the planter, but ridges were re-established at a height of 10–15 cm during the final cultivation. All tillage treatments, including no tillage, were cultivated once or twice between each row with 19-cm sweeps for weed control and aeration. Whole plots (crop rotation treatments) and subplots (tillage treatments) were replicated three times in a split-plot experimental design (Karlen et al., 1991). For this study, however, we have selected only the continuous corn treatment.

2.3. Tile drainage and measured NO_3–N

Subsurface drainage tiles were installed at a depth of 1.2 m between and in the center of each 0.4 ha plot in 1979, after recognizing in 1978 that long-term effects would be confounded by variability in soil drainage. To minimize soil disturbance, a trenchless drain plow was used to install the center drain tile, but lines between plots were installed using a trencher. Drain-tile spacing was 29.3 m in all plots, regardless of topographical position or apparent need for drainage. Border-tile lines are assumed to prevent cross contamination from surrounding plots. The center tile line in each plot was intercepted and connected to individual sumps for measuring subsurface drainage (tile flow) and collecting water samples for chemical analysis. To monitor tile flow on a continuous basis, each tile sump has a 110-V effluent pump, water-flow meter, and an orifice tube to collect water samples for analysis. The water-flow meters were connected to dataloggers for recording tile flow data. The orifice tube was designed to deliver ca. 0.2% of the tile water into a sampling bottle each time drainage water was pumped from the sump (Kanwar et al., 1997). Monitoring of NO_3–N and herbicide losses in the drainage water began in December 1988.

2.4. Production practices, N applied, and N in harvested grain

During the 1977–1992 period, 202 (kg N) ha^{-1}, as anhydrous ammonia, was knife applied between rows each spring just before planting. Annual broadcast P and K applications were 26 and 50 kg ha^{-1} for the period 1977–1982, respectively, and 17 and 66 kg ha^{-1}, respectively, for 1983–1992. An additional 4 : 6 : 12 kg ha^{-1} of N : P : K starter fertilizer was applied in a band each year when the corn was planted. Terbufos was applied at 1.2 (kg a.i.) ha^{-1} for insect control each year. Alachlor and atrazine were applied at rates of 2.2 and 2.8 (kg a.i.) ha^{-1} $year^{-1}$, respectively, for weed control; their movement to tile drainage was reported by Kanwar et al. (1997). All plots, including the no tillage primary tillage treatment, were cultivated once or twice during the growing season to provide additional weed control.

Commercially available corn hybrids ('Pioneer Brand 3780' for 1977–1983, 'Ames Best SX 37' in 1984, 'Pioneer Brand 3747' in 1985 and 1986, 'Pioneer Brand 3732' in 1987, and 'Golden Harvest 2343' for 1988–1992) were planted in 75 cm rows with a six-row planter. Each tillage plot consisted of 76 rows spaced 75 cm apart. Planting always began on the north side of each plot and ended on the south with two planter units 'turned off' in a 1.5-m grass border strip. Wheel traffic was consistent throughout the field, but since the combine used for harvest had a 2.3-m wheel base, every row had wheel traffic on one side and two of every six rows had wheel traffic on both sides, one or more times during the growing season. Grain yield was measured each year by harvesting three 3-row strips across each plot, weighing the grain, and subsampling for moisture determinations. Grain N concentrations were measured in 1992 by dry combustion with a Carlo–Erba Model NCS 1500 (Haake Buchler, Patterson, NJ) after grinding the grain to pass a 0.5 mm stainless steel screen. Annual N removal by the grain was estimated by adjusting the yield to zero g kg^{-1} water content and multiplying by the average 1992 grain N concentrations (12.9, 12.6, 12.2, and 11.3 (g N) kg^{-1} for moldboard plow, chisel plow, ridge-tillage, and no-tillage practices, respectively). Grain N concentrations were not measured during the other years, but the values for 1992 were within the range reported by Pierre et al. (1977) for corn grown in N-rate studies throughout Iowa, USA.

2.5. Soil C and N balance

The amount of fertilizer N immobilized in the soil organic-matter pool for the various primary tillage treatments was estimated based on changes in soil C between 1977 and 1988 or 1992. Calculations were made using individual plot data for the 0–5, 5–10, and 10–20 cm depths of sampling in the autumn of 1977, 1988, and 1992. An average of the changes computed for 1988 and 1992 was used for the overall N balance because the 1988 samples were collected following a severe drought that resulted in very low crop yields, while the 1992 sampling followed a highly productive year. Changes in soil C and immobilized N were computed using the following relationships:

$$\begin{aligned}&(\text{current organic C}) - (\text{baseline organic C})\\ &\quad = \Delta\text{C in g}\,(\text{kg}^{-1}\ \text{soil}); \qquad (1)\end{aligned}$$

$$\begin{aligned}&(\Delta\text{C in g}\,\text{kg}^{-1} \times (\text{kg soil})\,\text{ha}^{-1}\text{to depth of sampling})/\\ &\quad \text{C : N ratio} = \Delta\text{N in kg}\,\text{ha}^{-1}\end{aligned}$$

Statistical analyses were computed using a general linear model to determine if tillage treatments were significantly different at any of the sampling depths.

2.6. Simulation modeling

Version 3.25 of the RZWQM (USDA–ARS, 1995) was used to simulate the N balance (gains and losses) for the 15-year period (1978 through 1992) of continuous corn production. Development, theory, modification for tile drainage, and calibration of RZWQM for corn have been previously reported (USDA–ARS, 1995; Singh and Kanwar, 1995a, b; Nokes et al., 1996), but can be summarized as follows. For nitrate (NO_3–N) transport through the soil profile, a sequential partial displacement and mixing approach in 1 cm layer increments is used. This is based on the established concept of miscible displacement. Preferential flow in macropore channels is treated separately. An organic matter/nitrogen submodel (OMNI) is used for C and N cycling. Initial levels of soil organic matter, crop residue, other organic N, NO_3–N, and ammonium (NH_4–N) are provided as input data. Mineralization, nitrification, immobilization, denitrification, and volatilization of appropriate N forms are then computed. A multi-pool approach is used for organic matter cycling. Process rate equations are based on chemical kinetic theory and controlled by microbial population size and environmental parameters, including soil temperature, pH, water content, and salinity. Levels of soluble nutrients are used in estimating crop growth, nutrient loss in surface runoff, and movement through and below the root zone. The NO_3–N concentration in the subsurface drainage water is calculated as total mass of NO_3–N in the drained water divided by the drainage volume per unit area to the subsurface drain. The plant component uses environmental fitness (EVP) as a scaling factor to provide a measure of the suitability of the environment for providing plant needs. The EVP is computed as the product of current temperature fitness and the minimum of current water and N fitness. All factors are scaled between 0 and 1, with 1 representing the ideal conditions (Nokes et al., 1996).

The hydrology component of RZWQM version 1.0 was previously evaluated for this site by using tile drainage for 1990 to calibrate the model and then simulating the 1991 and 1992 drainage values for comparison with the measured values (Singh and Kanwar, 1995a). The earlier version of RZWQM was also used to simulate the effects of the four tillage practices on subsurface NO_3–N concentrations and losses (Singh and Kanwar, 1995b), but the model had not been previously used to compute an entire N balance for this research site.

Tillage effects were simulated with RZWQM using soil bulk density, residue cover, and the amount of crop residue incorporated in the surface horizon as measured in June 1991 (Table 1) as input data. Macroporosity was subjected to calibration for each tillage system. Field-measured values were considered to more accurately represent actual field conditions

Table 1
Surface (0 to 20 cm) properties measured in June 1991 and used as input for RZWQM simulation modeling of tillage effects (adapted from Singh and Kanwar, 1995a)

Soil property	Moldboard plow	Chisel plow	Ridge tillage	No tillage
Bulk density (Mg m^{-3})	1.38	1.41	1.38	1.50
Porosity (m^3 m^{-3})	0.48	0.47	0.48	0.43
Macroporosity (m^3 m^{-3})	0.0	0.0	0.0	0.004
Residue pools (mg kg^{-1})				
slow pool	700	450	310	140
fast pool	1000	700	480	215
Surface crust	present	no	no	no
Crop residue (Mg ha^{-1})	0.6	3.8	5.0	6.2

rather than the empirical functions available within RZWQM to estimate those parameters as a function of tillage.

The model was calibrated using the 1990 corn yield data to compute crop coefficients. Soil-test NO_3–N data reported by Karlen et al. (1991) for 1988 were used as the best available information for initiating the 1978 simulations. The model failed completely for 1988 and 1989 because of extremely low rainfall, so we have not reported any simulation results for those years. To compensate, simulations were made for two time periods, (1) from 1978 through 1987, and (2) 1990 through 1992. The simulation for 1990–1992 used the same crop coefficients, but initial soil test NO_3–N levels were based on 1990 measurements. For both, 1978–1987 and 1990–1992, seasonal weather and crop management information were provided as model input. Simulated profiles for NO_3–N, NH_4–N, denitrification, volatilization, runoff loss, seepage loss, N-uptake, N mineralization, and crop yield were obtained as output for the moldboard plow, chisel plow, ridge-tillage, and no-tillage treatments. The simulation results were evaluated to assess the effects of tillage practices on various components affecting the overall N budget. The model output was also used to compute differences between ridge- and the other primary-tillage treatments, which were then analyzed statistically using a paired *t*-test (SAS Institute, 1985).

3. Results

3.1. Measurement-based estimates

3.1.1. Grain yield and N removed

Corn-grain yields showed statistically significant differences ($P<0.0001$) among years, tillage practices, and for the tillage-by-year interaction (Table 2). Significant differences among years were highly correlated to the amount of rainfall received during June, July, and August. Simple correlation coefficients between yields for the plow, chisel, ridge till, and no-tillage treatments and rainfall received between June 1 and August 31 each year were 0.80, 0.70, 0.70, and 0.66, respectively. Correlations for those tillage treatments and the (July+August) rainfall were 0.76, 0.73, 0.72, and 0.69, respectively. Linear regression between mean grain yield for the four tillage treatments and rainfall received from June through August or (July+August) produced Eqs. (2) and (3), respectively:

$$\text{Grain yield}(\text{Mg ha}^{-1}) = 5.04 + 0.009274\ (\text{mm rainfall}) \quad r^2 = 0.53 \tag{2}$$

Table 2
Primary tillage effects on continuous corn yield from tile-drained Aquic Hapludolls in northeastern Iowa

Year	Rainfall[a] (mm)		Moldboard	Chisel	Ridge tillage	No tillage
	Apr–Nov	Jul–Aug	Yield (Mg ha^{-1})			
1978	843	210	9.16	7.90	7.45	7.36
1979	1000	510	10.03	9.60	9.22	8.99
1980	806	384	9.65	9.44	9.32	9.51
1981	808	277	10.25	9.91	9.96	9.57
1982	758	196	7.59	7.56	7.42	7.22
1983	1089	144	5.88	5.02	5.10	5.01
1984	641	94	6.14	5.57	5.19	4.97
1985	654	123	7.77	7.45	7.54	7.61
1986	809	216	10.29	10.60	9.95	9.78
1987	580	297	8.42	8.15	7.97	7.90
1988	472	155	5.42	5.43	4.63	4.56
1989	430	114	6.10	7.21	6.67	6.33
1990	1049	535	11.45	11.17	10.38	9.35
1991	933	184	9.24	8.76	7.95	7.33
1992	718	250	9.45	9.18	8.98	8.72
$LSD_{(0.01)}$	—	—	0.73			

[a] The 1951–1984 average annual precipitation was 844 mm, which included an average of 980 mm of snowfall (USDA-NRCS, 1995).

$$\text{Grain yield}(\text{Mg ha}^{-1}) = 5.63 + 0.009762\,(\text{mm rainfall}) \quad r^2 = 0.54 \tag{3}$$

The strong influence of summer rainfall and other weather factors (presumably temperature) on corn-grain yield at this location, is supported by Carlson (1990) who concluded that water availability and heat stress are the two most important weather-related variables affecting corn yields in Iowa.

Over the 15-year period, corn-grain yields for moldboard plow, chisel plow, ridge tillage and no tillage averaged 8.46, 8.20, 7.85, and 7.61 Mg ha^{-1}, respectively. Several factors (Karlen et al., 1994), including lower early-season soil temperature, increased potential for insect and disease pressure, and mechanical problems associated with stand establishment, presumably contributed to the lower long-term yields for the ridge tillage and no-tillage treatments for continuous corn production. Improved planting equipment and use of a corn–soybean rotation instead of continuous corn are two management choices that can be used to minimize the tillage-induced differences in crop yield (Karlen, 1989; Karlen et al., 1991).

Based on these long-term yields and the grain N concentrations which were measured at this research site in 1992, the estimated amount of N removed with corn grain after 15 years totaled 1543, 1416, 1389, or 1224 kg ha^{-1} for the moldboard plow, chisel plow, ridge-tillage, or no-tillage practices, respectively. The differences in grain N removal among the four tillage treatments were significant ($P<0.001$), and when divided by the amount of fertilizer N applied during those 15 years (3090 kg ha^{-1}) would account for 50, 46, 45, or 40% of the fertilizer N, respectively.

3.1.2. Soil-nitrogen balance

A nitrogen balance in the soil above the tile lines associated with the four long-term tillage practices was computed using the changes in total organic C values. Soil samples collected in autumn 1977 showed that total organic C levels in plots assigned to the various tillage treatments were not significantly different for the 0–5, 5–10, and 10–20 cm sampling depths (Table 3). The average soil carbon content for the entire site within the surface 0–20 cm was 17.0 g kg^{-1}, which would have been between 55 and 70% of that expected for surface soil horizons at this

Table 3
Changes in surface C and N content after 11 and 15 years of moldboard plow, chisel plow, ridge tillage, or no tillage for continuous corn production

Tillage	*Soil organic carbon* (g kg^{-1})			Δ *Carbon* (g kg^{-1})		*C* : *N ratio*		Δ *Nitrogen* (kg ha^{-1})	
	1977	1988	1992	1977– 1988	1977–1992	1988	1992	1977–1988	1977–1988
0–5 cm									
Moldboard	15.5a[a]	19.2b	23.7c	3.6b	8.2c	12.4b	12.3a	182b[b]	416c
Chisel	17.4a	23.2ab	29.1bc	5.8ab	11.7bc	13.2ab	13.2a	275ab	565bc
Ridge tillage	17.3a	24.9a	32.9ab	7.6a	15.6ab	13.8a	12.6a	345a	771ab
No tillage	17.6a	24.0a	37.3a	6.4ab	19.7a	13.4ab	13.2a	300ab	932a
5–10 cm									
Moldboard	18.0a	19.2b	23.6a	1.2a	5.5a	13.4a	11.9a	58a	302a
Chisel	19.6a	22.3a	28.9a	2.7a	9.3a	13.1a	12.8a	136a	487a
Ridge tillage	18.8a	20.6ab	25.5a	1.8a	6.7a	13.6a	12.7a	85a	352a
No tillage	18.0a	19.6ab	26.0a	1.6a	8.0a	13.4a	12.0a	77a	433a
10–20 cm									
Moldboard	16.0a	19.9a	22.3a	3.9a	6.3a	13.3a	12.1a	394a	702a
Chisel	16.9a	20.9a	26.0a	4.1a	9.2a	13.4a	12.7a	410a	1000a
Ridge tillage	16.1a	18.6a	23.3a	2.5a	7.2a	13.0a	12.4a	263a	808a
No tillage	16.2a	18.3a	22.9a	2.1a	6.7a	12.9a	12.1a	220a	751a

[a] Values for each depth and year followed by the same letter are not different at the 0.05 probability level.

[b] Values computed using soil bulk densities of 1.25, 1.30, and 1.35 Mg m^{-3} for the 0–5, 5–10, and 10–20 cm sampling depths, respectively, based on Logsdon et al. (1993) and USDA-NRCS (1995).

site (USDA–NRCS, 1995). The low soil-carbon values are presumably accurate, since the land was being managed with traditional, intensive tillage practices (fall moldboard plowing with multiple secondary tillage operations for seedbed preparation), relatively low fertilizer and lime inputs, and there was no manure applied on the farm for several years before it was purchased and developed as an Outlying Research Center for Iowa State University in 1976 (Dr. Mark Honeyman, personal communication, 1997).

Soil samples were collected a second and third time in the autumn of 1988 and 1992 to measure soil-carbon content. The 1988 sampling showed significant differences among tillage treatments within the 0–5 and 5–10 cm increments after 11 years of continuous corn production (Table 3). Samples collected in 1992 showed significant C differences due to tillage treatment in the surface 5 cm, but not in the 5–10 or 10–20 cm depth increments. For both sampling dates, organic-C content was significantly lower in plots that were moldboard plowed, although even with moldboard plowing, there was an increase in soil organic C since 1977. The magnitude of change in soil organic C between 1977 and 1988 ranged from 3.6 to 7.6 g kg^{-1}, while differences measured between 1977 and 1992 ranged from 8.2 to 19.7 g kg^{-1}. Several factors presumably contributed to the observed differences in organic-C accumulation between 1977 and 1988 or 1977 and 1992. This included the use of improved no-tillage planting equipment, better stand establishment, and better yields. The 1988 soil sampling also followed a severe drought, which resulted in the lowest grain yield for the 15-year period (5.0 Mg ha^{-1}). This may have reduced above- and below-ground plant biomass and subsequent C inputs to the surface soil. In contrast, 1992 had a much higher grain yield (9.1 Mg ha^{-1}), presumably resulting in greater C additions to the surface soil.

Based on the changes in soil organic C and the C : N ratios, which were significantly different among tillage treatments only within the 0–5 cm increment for the 1988 sampling (Table 3), the amount of N accounted for by Eq. (1) ranged from 597 to 821 kg N ha^{-1} in the surface 20 cm in 1988 and from 1420 to 2116 kg N ha^{-1} in 1992 (Table 3). As a percentage of total applied fertilizer N, those values represent 19–26% in 1988 or 46–68% in 1992.

For estimating the long-term N balance, we suggest that the ΔN values, computed using measured changes in organic C (Table 3), may represent extremes, since the 1988 sampling followed a drought and the 1992 sampling followed a year with excellent growing conditions. Therefore, we suggest using the average ΔN (in kg ha^{-1}) for 1988 and 1992. Based on this assumption, changes in soil organic matter between 1978 and 1992 could account for 33, 46, 42, or 44% of the fertilizer N applied to moldboard plow, chisel plow, ridge-tillage, and no-tillage treatments, respectively. As shown in Table 3, differences in N accumulation among tillage treatments were statistically significant only within the 0–5 cm depth, where the moldboard plow plots had a significantly lower change in N than the ridge-tillage treatment in 1988 or the ridge tillage and no-tillage treatments in 1992. When the amount of N, estimated to have been removed by the corn grain, is added to the N that is presumably incorporated into soil organic matter, we can now account for 83–92% of the fertilizer N applied between 1978 and 1992.

3.1.3. N losses in tile lines

Kanwar et al. (1997) reported that NO_3–N losses in tile drainage water from this site ranged from 58 to 108, 63 to 76, and 11 to 20 kg ha^{-1} for 1990, 1991, and 1992, respectively, with no significant differences among tillage treatments. The large differences among these years were directly proportional to the amount of rainfall received between April and November of each year (Table 2).

Additional assumptions about drainage from these tiled soils are required to complete the long-term N balance. First, assume that drainage losses measured for 1990 were representative of years when seasonal rainfall exceeded 1000 mm (1983 and 1990). Second, assume that losses measured for 1991 represent years with seasonal rainfall between 850 and 1000 mm (1979 and 1991). Third, assume that losses measured for 1992 represent years with seasonal rainfall between 475 and 850 mm (1978, 1980–1982, 1984–1987, and 1992), and finally, assume no losses for 1988 or 1989 when seasonal rainfall was less than 475 mm and there was essentially no tile flow. Based on these four assumptions, we can account for 467, 369, 352, and 466 kg N ha^{-1} in drainage losses for the moldboard plow, chisel plow, ridge-tillage, and no-tillage treatments, respectively, during the 15-year continuous corn production. Adding the tile drainage losses to those estimated above for changes in soil organic matter and grain removal, we can account for 98, 104, 99, and 99% of the fertilizer N applied to the four tillage treatments, respectively. The remaining fraction of applied N can easily be accounted for by denitrification (Meisinger and Randall, 1991), volatilization, or possibly leaching past the tile-drain lines.

3.2. Simulation studies of N dynamics

Several computer simulations using Version 3.25 of RZWQM were conducted to help assess the fate of fertilizer N applied to the four tillage treatments between 1978 and 1992. The model was calibrated against observed grain yield, with the predominant outliers being associated with years when rainfall was extreme. After fitting the yield data, predictions of soil profile NO_3–N, NH_4–N, denitrification, seepage loss, N-uptake, N mineralization, and crop yield were computed. Values similar to those presented for the ridge-tillage treatment (Table 4) were obtained for the moldboard-plow, chisel-plow, and no-tillage treatments. There was no volatilization or runoff loss predicted for any of the tillage practices, since the fertilizer N was applied as anhydrous ammonia at a depth of 22.5 cm.

Differences among the tillage treatments for the various components affecting the overall N balance were computed and used to examine the potential effects of changing tillage practices on soils requiring drainage for optimum crop production. Compared to ridge-tillage, moldboard-plow treatments had significantly higher mineralization rates and lower leaching losses (Table 5). The chisel-plow treatment had significantly lower denitrification and profile NH_4–N levels, while the no-till treatment had significantly higher profile NO_3–N and seepage loss to the drainage tile. Predicted grain yields were not significantly different among tillage treatments, although the pattern of differences was similar to that measured and reported by Kanwar et al. (1997).

The simulation effort encountered some problems that might identify areas for future model improvement. With regard to hydrology, RZWQM (v. 3.25) included movement of water through the soil profile and out of the tile-drainage lines. In continuous simulations, the model failed to predict tile flows accurately because of inaccurate predictions of water-table height. One reason is that the model does not have a freeze/thaw component and the water-table height during winter months is calculated as in normal months, but with minimal evapotranspiration. The

Table 4
Soil profile of N sources and sinks predicted by RZWQM for continuous corn grown using ridge-tillage practices

Year	N source/sink (kg ha^{-1})						Corn yield	
	NO_3	NH_4	mineralized	seepage	denitrified	uptake	predicted	measured
1978	84	0.0	23	2	2	194	9426	7449
1979	44	0.4	23	68	12	172	8054	9222
1980	57	1.6	62	10	23	204	9135	9321
1981	73	1.3	49	14	26	184	8702	9960
1982	72	0.3	55	15	50	184	7534	7420
1983	81	2.1	65	37	35	172	7123	5099
1984	96	1.5	80	12	49	194	8182	5189
1985	115	0.6	98	8	50	211	8931	7541
1986	145	0.5	99	19	33	206	9771	9950
1987	180	0.8	100	9	8	238	9897	7970
1988	—[a]	—	—	—	—	—	—	4635
1989	—	—	—	—	—	—	—	6669
1990	154	8.2	19	83	2	224	10165	10383
1991	84	0.6	35	64	12	222	8357	7954
1992	56	0.9	53	8	11	247	11422	8979

[a] Missing values because severe drought caused model to fail.

Table 5
Differences in RZWQM version 3.25 output parameters for long-term ridge-tillage versus moldboard-plow, chisel-plow, or no-tillage treatments in northeast Iowa, USA

Parameter	Moldboard plow[a] kg ha^{-1}	Sig.[b] P > |t|	Chisel plow[a] kg ha^{-1}	Sig. P > |t|	No tillage[a] kg ha^{-1}	Sig. P > |t|
NO_3-N	−13	0.210	2	0.831	19	0.030
NH_4-N	0.6	0.382	−0.8	0.004	0	1.000
Mineralized N	21	0.010	7	0.119	−2	0.706
Seepage N loss	−16	0.001	0.9	0.682	10	0.016
Denitrifed N	14	0.070	−11	0.004	−2	0.457
Predicted yield	482	0.179	96	0.742	−84	0.666

[a] These are measured differences computed as: (tillage x)−(ridge-tillage treatment).

[b] Probability level at which the value for the given tillage treatment is significantly different from that associated with the ridge tillage treatment.

model then predicted a drop in the water-table in April, when in reality it should remain close to the tile-line depth. This model weakness was confirmed by the tile-flow data collected during the early spring (Kanwar et al., 1997). The hydrology problems subsequently cause errors in tile-flow and water-table predictions. The errors are cumulative in continuous simulations because the water-table height is not reset for subsequent years.

Hydrology problems with the model also resulted in the high denitrification estimates for 1981 through 1987 (Table 4). The chemistry of RZWQM is dependent upon the accuracy of hydrologic predictions, so when predicted losses of NO_3–N through the tile lines were low, the net result was an increase in the amount of N available in the soil profile for either plant uptake or denitrification. Inaccurate denitrification predictions and errors in the other N pools appeared to become cumulative if continuous simulations (i.e. 1978–1987) were made. Running the model for single-year simulations prevented the compound errors, but would not be as useful for examining the long-term effects of various management treatments.

The organic matter pools for RZWQM are defined as slow, medium, and fast. For our simulations, default values given in the technical documentation (USDA–ARS, 1995) were used as the initial pool values. These organic matter pools (especially the fast pool) have a major effect on nitrate in the soil profile. Due to the interactive nature of these pools in soil, inaccurate predictions in one process results in inaccuracy in many other parameters. These factors appear to have contributed to the extreme variability in mineralization and profile NO_3–N estimates. These parameters must be confirmed for the conditions encountered wherever the RZWQM model is being used.

Yield estimates made within RZWQM are a function of soil-water availability to the plant and the N uptake. There were a few outliers, but the average predicted yields were within ±10% of the observed yields for each tillage treatment. This agreement resulted in an average r^2 of 0.78 for the four tillage treatments. The RZWQM predicted total N uptake for 1990–1992 did not correlate well (r=0.27; P<0.4) with the values reported by Kanwar et al. (1997). The model consistently predicted much higher total N accumulation than was measured in samples collected from the various tillage treatments. As a result of over-predicting total N accumulation, when the 0.64–0.78 factor, suggested by Schepers and Mosier (1991) to estimate grain N, was applied to the 1992 simulation results, the estimated grain N removal was ≈33% higher than the 105 kg ha^{-1} measured for that year.

4. Discussion

The change in soil organic C concentrations after 11 or 15 years for all four tillage treatments at this location was greater than that reported after 8 years of continuous corn in east-central Nebraska (Varvel, 1994). Factors contributing to this difference include using higher maximum N fertilizer rates (206 vs. 180 kg ha^{-1} $year^{-1}$), producing higher average corn yields (8.0 vs. 6.2 Mg ha^{-1} $year^{-1}$), having more annual precipitation (845 vs. 686 mm), and having a site where the initial soil organic C pools were more depleted because of prior management practices. Relative consistency between the 1988 and 1992 analyses, which were made before N rates were reduced (Table 3), and with measurements in 1996, which showed organic C concentrations of 23.7, 22.0, and 17.3 g kg^{-1} for the 0–7.5, 7.5–15, and 15–30 cm depth increments, respectively, confirm that soil organic matter (based on organic C measurements) has increased at this site since 1977.

The N budget demonstrates an important reason for continuing to conduct long-term field research (Jenkinson, 1991), specifically showing how the input and output records can be used to compute nutrient balances. Our budget shows that continuous corn production is not efficient with regard to capturing recently applied fertilizer N, since only 40–50% of the annual application N could be accounted for by crop removal. However, those estimates are within the range reported for midwestern U.S. soils by several researchers using isotopically labeled N (Sanchez and Blackmer, 1988; Timmons and Cruse, 1990). An important factor for assessing relationships between soil and crop production practices and potential off-site water quality, however, was the 29–44% of the applied fertilizer N that could be accounted for by changes in soil organic matter pools. Increases in soil organic matter were apparent for all tillage treatments, suggesting that if excess N is available and if soil management practices preserve C from crop residues and/or root systems, a portion of the available N will be immobilized and, therefore, not available for immediate leaching loss. However, the C pools are subject to mineralization with subsequent leaching of the N, especially if periods of low rainfall are followed by excessively wet periods (i.e. 1988–1991). With regard to changing from moldboard-plow or chisel-plow to ridge- or no-tillage practices to mitigate potential off-site water quality impacts of agriculture, our results suggest that simply changing tillage practice, without changing cropping sequence, timing and method of N application, or N input source will have minimal impact on N loss to surface or subsurface waters.

The simulation effort was informative, primarily because it helped identify several areas where additional understandings of N cycling processes need to be incorporated into the model. Predicted seepage losses of N were similar to those measured and reported by Kanwar et al. (1997). Estimates of total N accumulation were much higher than the values reported by Kanwar et al. (1997) for 1988–1992. Major discrepancies between predicted and observed soil profile NO_3–N concentrations suggest that RZWQM does not accurately capture the dynamics occurring among the various C and N pools within the soil. As shown by a very simple N budget and differences in organic-C concentrations for 1988 and 1992, these pools are dynamic, responsive to tillage and, therefore, not easy to simulate.

Our simulation efforts were hindered by the lack of breakpoint precipitation data for 1978 through 1989, although this is not unusual and can be compensated for by the model. The low amount of rainfall received during 1988 and 1989 (Table 2) also caused the RZWQM model to fail because of unrealistic decreases in water-table depth. The modeling effort was useful for identifying areas where data now being collected from this long-term research site can be used to improve RZWQM, but we do not recommend using the current version to predict the fate of fertilizer N applied to various tillage treatments.

5. Summary and conclusions

A simple carbon-based N budget developed after 15 years of continuous corn grown on a tile-drained soil accounted for 98–104% of the fertilizer N which was applied during those years. Increased C content within the top 20 cm of the profile showed that 33–46% of the applied fertilizer N could be accounted for by changes in the amount of soil organic matter. Approximately 40–50% of the fertilizer N could be accounted for by grain removal and 11–15% through estimated loss via the tile drainage lines. Version 3.25 of RZWQM accurately simulated corn yield, but there were large discrepancies in total N accumulation and the various pools within the soil system for all four tillage treatments. Profile NO_3–N, mineralization, seepage loss through tile drainage, and denitrification estimates were generally excessive and not satisfactory for predicting the fate of applied N. Finally, simply adopting less intensive tillage practices, such as ridge tillage, without concurrent changes in N fertilization rates, methods of application, and associated soil- and crop-management strategies will not reduce the potential for adverse water quality effects by production agriculture.

Acknowledgements

Journal Paper No. J-17223 of the Iowa Agricultural and Home Economics Experiment Station, Ames IA. Project No. 3415. A contribution from the Management Systems Evaluation Areas (MSEA) Program, a joint USDA–Agricultural Research Service (ARS) and USDA–Cooperative State Research Extension and Education Service (CSREES) program under the Water Quality Initiative.

References

Ahmad, N., Kanwar, R.S., Kaspar, T.C., Baily, T.B., 1992. Effects of soil moisture submergence and a water table on vegetative growth and nutrient uptake of corn. Trans. ASAE 35, 1173–1177.

Carlson, R.E., 1990. Heat stress, plant-available soil moisture, and corn yields in Iowa: A short- and long-term view. J. Prod. Agric. 3, 293–297.

Fletcher, D.A., 1991. A national perspective. In: Follett, R.F., Keeney, D.R., Cruse, R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Inc., Madison, WI, pp. 9–17.

Gast, R.G., Nelson, W.W., Randall, G.W., 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen applications to continuous corn. J. Environ. Qual. 7, 258–261.

Jenkinson, D.S., 1991. The Rothamsted long-term experiments: Are they still of use? Agron. J. 83, 2–10.

Kanwar, R.S., Johnson, H.P., Baker, J.L., 1983. Comparison of simulated and measured nitrate losses in the tile effluent. Trans. ASAE 26, 1451–1457.

Kanwar, R.S., Colvin, T.S., Karlen, D.L., 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. J. Prod. Agric. 10, 227–234.

Karlen, D.L., 1989. Tillage and planting system effects on corn emergence from Norfolk loamy sand. Appl. Agric. Res. 4, 190–195.

Karlen, D.L., Berry, E.C., Colvin, T.S., Kanwar, R.S., 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun. Soil Sci. Plant Anal. 22, 1985–2003.

Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. In: Sparks, D.L. (Ed.), Adv. Agron. Vol. 53, Academic Press, Inc., New York, N.Y., pp. 1–45.

Logsdon, S.D., Jordahl, J.L., Karlen, D.L., 1993. Tillage and crop effects on ponded and tension infiltration rates. Soil Tillage Res. 28, 179–189.

Meisinger, J.J., Randall, G.W., 1991. Estimating nitrogen budgets for soil-crop systems. In: Follett, R.F., Keeney, D.R., Cruse R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am. Inc., Madison, WI, pp. 85–124.

Nokes, S.E., Landa, F.M., Hanson, J.D., 1996. Evaluation of the crop growth component of the root zone water quality model for corn in Ohio. Trans. ASAE 39, 117–1184.

Pierre, W.H., Dumenil, L., Jolley, V.D., Webb, J.R., Shrader, W.D., 1977. Relationship between corn yield, expressed as a percentage of maximum, and the N percentage in the grain. I. Various N-rate experiments. Agron. J. 69, 215–220.

Power, J.F., Schepers, J.S., 1989. Nitrate contamination of groundwater in North America. Agri., Ecosys. Environ. 26, 165–187.

SAS Institute Inc., 1985. The *t*-test procedure. SAS User's Guide: Statistics, Version 5 edn. Cary, NC 956 pp.

Sanchez, C.A., Blackmer, A.M., 1988. Recovery of anhydrous ammonia-derived nitrogen 15 during three years of corn production in Iowa. Agron. J. 80, 102–108.

Schepers, J.S., Mosier, A.R., 1991. Accounting for nitrogen in nonequilibrium soil-crop systems. In: Follett, R.F., Keeney, D.R., Cruse R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Inc., Madison, WI, pp. 125–138.

Shaffer, M.J., Halvorson, A.D., Pierce, F.J, 1991. Nitrate leaching and economic analysis package (NLEAP): Model description and application. In: Follett, R.F., Keeney, D.R., Cruse, R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Inc., Madison, WI, pp. 285–322.

Singh, P., Kanwar, R.S., 1995a. Modification of RZWQM for simulating subsurface drainage by adding a tile flow component. Trans. ASAE 38, 489–498.

Singh, P., Kanwar, R.S., 1995b. Simulating NO_3–N transport to subsurface drain flows as affected by tillage under continuous corn using modified RZWQM. Trans. ASAE 38, 499–506.

Timmons, D.R., Cruse, R.M., 1990. Effect of fertilization method and tillage on nitrogen-15 recovery by corn. Agron. J. 82, 777–784.

USDA–ARS, 1995. Root Zone Water Quality Model (RZWQM). V. 3.5. Technical Documentation. USDA–ARS Great Plains Systems Research Unit, Ft. Collins, CO.

USDA–NRCS, 1995. Soil Survey of Floyd County Iowa. U.S. Dept. of Agric., Natural Resources Conservation Service, Washington, D.C.

Varvel, G.E., 1994. Rotation and nitrogen fertilization effects on changes in soil carbon and nitrogen. Agron. J. 86, 319–325.