Agricultural Systems 106 (2012) 59–71

Contents lists available at SciVerse ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Extending results from agricultural fields with intensively monitored data to surrounding areas for water quality management

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ARTICLE INFO

Article history:
Received 30 September 2010
Received in revised form 22 September 2011
Accepted 30 October 2011

Keywords:
Nitrogen
Nitrate
Tile drainage
Tileflow
Simulation model
Decision support system

ABSTRACT

A 45% reduction in riverine total nitrogen flux from the 1980–1996 time period is needed to meet water quality goals in the Mississippi Basin and Gulf of Mexico. This paper addresses the goal of reducing nitrogen in the Mississippi River through three objectives. First, the paper outlines an approach to the site-specific quantification of management effects on nitrogen loading from tile drained agriculture using a simulation model and expert review. Second, information about the net returns to farmers is integrated with the nitrogen loading information to assess the incentives to adopt alternative management systems. Third, the results are presented in a decision support framework that compares the rankings of management systems based on observed and simulated values for net returns and nitrogen loading. The specific question addressed is how information about the physical and biological processes at Iowa State University's Northeast Research Farm near Nashua, Iowa, could be applied over a large area to help farmers select management systems to reduce nitrogen loading in tile drained areas. Previous research has documented the parameterization and calibration of the RZWQM model at Nashua to simulate 35 management system effects on corn and soybean yields and N loading in tileflow from 1990 to 2003. As most management systems were studied for a 6 year period and in some cases weather had substantial impacts, a set of 30 alternative management systems were also simulated using a common 1974–2003 input climate dataset. To integrate an understanding of the economics of N management, we calculated net returns for all management systems using the DevTreks social budgeting tool. We ranked the 35 observed systems in the Facilitator decision support tool using N loading and net returns and found that rankings from simulated results were very similar to those from the observed results from both an onsite and offsite perspective. We analyzed the effects of tillage, crop rotation, cover crops, and N application method, timing, and amount for the 30 long term simulations on net returns and N loading. The primary contribution of this paper is an approach to creating a quality assured database of management effects on nitrogen loading and net returns for tile drained agriculture in the Mississippi Basin. Such a database would systematically extend data from intensively monitored agricultural fields to the larger area those fields represent.

1. Introduction

Agriculture faces significant challenges meeting the world's food, fiber, and fuel needs while reducing environmental impacts. The general problem addressed in this paper is how to provide better information to farmers about the impacts of management decisions on offsite agrichemical loadings. The specific question is: How can the research, extension, and conservation community systematically quantify management impacts on nitrogen loading and net returns from tile drained agriculture, and apply that information for field scale decision making?

Abbreviations: MLRA, Major Land Resource Area; CC, continuous corn; CP, chisel plow; CS, corn, soybean rotation with corn in even years; SC, soybean, corn rotation with soybean in even years; LCD, localized compaction and doming; LSNT, late-spring nitrate test; MP, moldboard plow; NT, no till; RT, ridge till; SM, swine manure; UAN, urea ammonium nitrate; RMSE, root mean square error; CSGs, Conservation System Guides.

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0308-521X/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.agsy.2011.10.010

The National Academy of Engineering identified managing the nitrogen cycle as one of the Grand Challenges of Engineering (NAE, 2008). Increased N raises the risks to human health and the health of water bodies, increases treatment costs for drinking water and contributes to hypoxia in the Gulf of Mexico. According to the Gulf Hypoxia Action Plan 2008 (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008, p. 22):

Significant reductions in nitrogen and phosphorus are needed. To achieve the Coastal Goal for the size of the hypoxic zone and improve water quality in the Basin, a dual nutrient strategy targeting at least a 45% reduction in riverine total nitrogen load and in riverine total phosphorus load, measured against the average load over the 1980–1996 time period, may be necessary.

and later (p. 44):

Understanding the most efficient and cost-effective conservation practices and management practices to reduce nutrient loads is central to the success of nutrient reduction strategies.

Agriculture is certainly not the only source of nitrogen to the Gulf, but reducing N loading in the northern Midwest is a critical issue, as this area produces high rates of N loading to the Mississippi (Heinz Center, 2002, pp. 46–47). Tile drained agriculture, in particular, requires a focus on N management, as the drains "short-circuit" soil water high in nitrate into streams. Unlike erosion, there are no visible signs, so farmers and conservationists cannot develop an intuitive sense for the relationship between management and N loading. In a study from two Minnesota watersheds, Petrolia and Gowda (2006) point out that controlling N loading in tile drained areas is likely to be a critical component of efforts to control hypoxia in the Gulf of Mexico, that tile drained processes should be explicitly modeled, and that certain nutrient management policies are only effective on tile drained land.

The foundation for understanding natural systems, and the effects of human activities on those systems, is observed data. As a guide to the practical management of those systems however, observed data is almost always limited, so decision making is not straightforward even on intensively studied areas. This paper outlines a process for improving the technical information about management effects on water quality provided to producers.

Farmers focus on agronomic and business issues in agricultural production. To reduce water quality problems from cropland, ultimately farmers need to adopt management systems that reduce N loading on a field by field basis. Delivering technical information requires trained specialists, often private consultants, Extension Agents, and NRCS Conservationists. Many in the conservation community are skilled at distilling research into guidelines or pithy decision rules. However, as the complexity of modern agriculture increases and the list of resource concerns expands, it becomes increasingly difficult for a conservationist to assimilate research findings, interpret, and apply those findings to a particular farmer's conditions while meeting other job demands. Simulation models provide an option for extending results and applying these to a larger set of fields, but effective and efficient application of models require yet another skill set, investment of time to parameterize, and the outputs can be difficult to interpret, particularly if multiple resource problems are being evaluated. In some cases there is a need for multiple models which further increases the complexity of the problem.

As shown on the top in Fig. 1, currently researchers publish results directly in the literature and Extension Agents and NRCS National, State, and Field Staffs are expected to interpret that information to farmers and help farmers apply that understanding under local conditions. To build a solid scientific foundation for conservation, publishing results in the literature is clearly essential. But when the range of subjects and depth of understanding required of conservationists becomes too large and complex for a conservation agency, let alone a field level conservationist to digest, an alternative approach is needed. We propose that for particularly problematic areas a database of results could capture the important relationships and simplify the Conservationist's job.

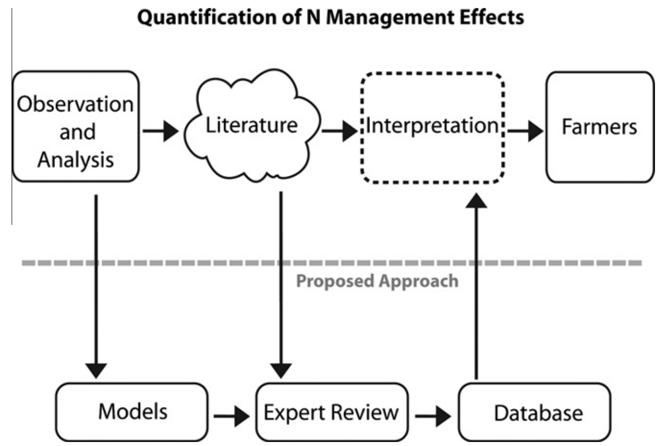

Fig. 1. Increasing complexity requires a more systematic approach in applying science to natural resource decision-making.

Information technology has advanced to the point where it will soon be feasible for many specialists, with various backgrounds, to collaborate systematically in addressing critical resource management issues that require interdisciplinary cooperation. A new, more integrated and systematic approach is needed that allows for increased collaboration by specialists (Heilman et al., 2002). A specialist or team of specialists would calibrate a comprehensive simulation model to quantify expected management effects, the estimates are then quality assured by local experts and used to populate a database for strategic decision-making. The task of the conservationist is then to interpret the database of estimated effects to farmers either through a specific DSS tool or incorporated into an N index tool (Delgado et al., 2008) specifically for tile drained agriculture. A nine step process for creating and applying such a database is shown in Fig. 2. The rest of this paper describes the application of Steps 1–5 and 8 in that process, based on an intensively monitored field scale research site.

2. Methods

2.1. Problem definition (Steps 1 and 2)

The foundation for this study is a dataset from Iowa State University's Northeast Research Center near Nashua, IA (43.0 N, 92.5 W), hereafter referred to as "Nashua". The robust dataset includes 14 years (1990–2003) of weather records, corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) yields, tileflow, and N concentration in drainage. According to Bakhsh et al. (2007), slopes at Nashua range from 0% to 8%, which corresponds to the slope groups A, B, and C (0–2%; 2–5%; and 5–9%). For this study we assume that Nashua represents land with similar soils and slopes found within the Natural Resources Conservation Service (NRCS) Major Land Resource Area 104, Eastern Iowa and Minnesota Till Prairies. The NRCS (2006) documents 2130 km^2 of Kenyon soils, 1080 km^2 of Readlyn soils, 1580 km^2 of Floyd soils, and 2490 km^2 of Clyde soils. Fig. 3 shows Nashua and the distribution of those soils in MLRA 104, most of which is in the 104.1 Common Resource Area.

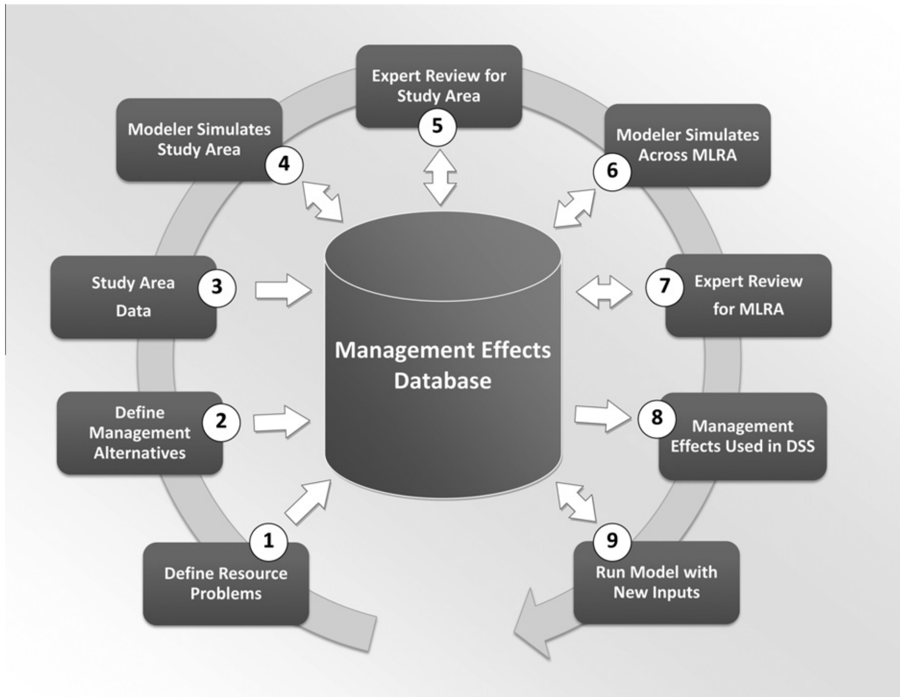

Fig. 2. Steps in the construction of a Conservation Effects Database.

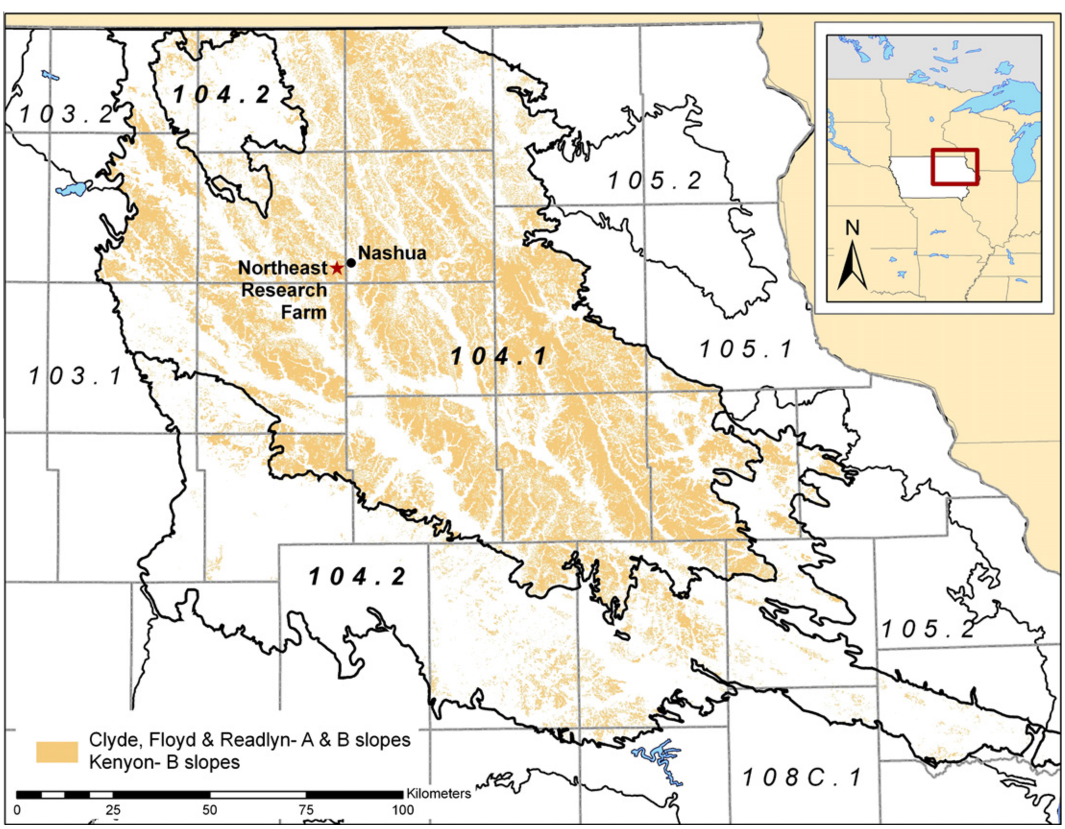

Fig. 3. Occurrence of Clyde, Floyd, Readlyn A and B slopes and Kenyon B slopes in Common Resource Areas 104.1 and 104.2 in northeastern Iowa.

In a preliminary effort, NRCS conservation planners identified a set of management systems for the primary soil and slope groups in MLRA 104.1 that addressed known resource problems (Table 1). Some grouping for simplification is possible. Table 2 shows the other soil and slope groups in MLRA 104.1 that the NRCS classified as capable of using the same combinations of management subsys-

Table 1
Number of management subsystems to address resource concerns in Major Land Resource Area 104.1.

Primary soil/slope group	Crop rotation Tillage system combinations	Nutrient systems	Pesticide systems	Conservation practices	Total no. of systems
Kenyon B	4	5	1	4	80
Kenyon C	4	5	1	4	80
Clyde A	3	5	1	2	30
Clyde B	3	5	1	4	60
Coland A	3	5	1	4	60
Provitin B	3	5	1	6	90
Marshan A	3	5	1	4	60
Olin B	4	5	1	4	80
Olin C	4	5	1	4	80
Rockton B	4	5	1	4	80
Rockton C	4	5	1	4	80
Marlene C	1	5	1	2	10
Marlene D	1	5	1	2	10
Marlene E	1	5	1	2	10
Marlene F	1	5	1	2	10

Table 2
Calculation of the number of management systems to simulate for Major Land Resource Area 104.1 based on soil and slope groups.

Primary soil/slope group	Similar soil slope groups (having the same management systems)	# of soils	# of systems	# of simulations required
Kenyon B	Bassett B, Ostrander B, Racine B, Aredale B	5	80	400
Kenyon C	Bassett C, Ostrander C, Racine C, Aredale C	5	80	400
Clyde A	Floyd A, Maxfield A, Klinger A, Oran A, Readlyn A, Tripoli A	7	30	210
Clyde B	Floyd B, Maxfield B, Klinger B, Oran B, Readlyn B, Tripoli B	7	60	420
Coland A	Spillville A	2	60	120
Provitin B	Cresco B, Lourdes B	3	90	270
Marshan A	Lawler A	2	60	120
Olin B	Saude B, Sparta B, Finchford B	4	80	320
Olin C	Saude C, Sparta C, Finchford C	4	80	320
Rockton B	Winneshiek B	2	80	160
Rockton C	Winneshiek B	2	80	160
Marlene C	Sogn C, Emeline C	3	10	30
Marlene D	Sogn D, Emeline D	3	10	30
Marlene E	Sogn E, Emeline E	3	10	30
Marlene F	Sogn F, Emeline F	3	10	30
Total		55	820	3020

tems as in Table 1. Clearly this is an issue prone to combinatorial explosion, as over 3000 management system/soil and slope combinations were identified, prior to consideration of climate.

2.2. Nashua study site (Step 3)

Kanwar (2006) provides a summary of nitrate research results at Nashua from 1989 to 1999, and Bakhsh et al. (2010) report results from 2001 to 2005. There are 36–0.4 ha plots in a randomized complete block design, with 6 years in each set of treatments. Initially, research focused on four tillage methods (moldboard plow, chisel plow, ridge-till, and no-till) and three crop rotations (continuous corn, corn–soybean, soybean–corn) on three plot replicates each. N was applied as anhydrous ammonia on all corn crops. After 1990, additional instrumentation allowed research at Nashua to address management effects on nitrogen in tileflow for 3 years with the initial tillage-rotation set of treatments.

Beginning in 1993, UAN (urea ammonium nitrate) was applied in corn years as fertilizer. From 1993 through 1998, the main focus was N management, including liquid swine manure, N rates, and using the late spring nitrate test (LSNT) to determine the N fertilizer rate. Only two tillage practices were applied (chisel plow and no-till) to accommodate the additional N management treatments. From 1999 through 2003, the focus of the study was manure application rate, timing, and method. Manure application rates were based on N or P needs for both phases of a corn–soybean rotation, either in the fall or spring. Each cropping season received manure and/or UAN liquid fertilizer. Table 3 provides a detailed list of the 35 treatments studied at Nashua between 1990 and 2003. The list is as detailed as possible, with corn and soybean rotations split depending on whether the corn was grown in an even (corn–soybean) or odd (soybean–corn) year. Malone et al. (2009) discuss some possible reasons for differences in corn yields among years. In some transition years N management differed, and those years were split out as separate management systems.

The primary soils at Nashua are Kenyon loam (Fine-loamy, mixed, superactive, mesic Typic Hapludolls), Readlyn loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and Floyd loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls). These soils are moderately well to poorly drained, benefit from subsurface drainage, lie over loamy glacial till, and belong to the Kenyon–Clyde–Floyd soil association. Of the 36 plots, 6 were not simulated (8, 17, 20, 27, 30 and 31) because of very high or low drainage, including two plots containing the heavier Clyde silty clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls), but there were still at least two replicates for each treatment (Ma et al., 2007a). A map of the soil types at the Nashua study site appears as Fig. 1 in Ma et al. (2007c) and additional information on each soil can be found in the official soil series descriptions (NRCS, 2006).

Nashua is a very rich dataset, but some data gaps remain. Resource limitations at Nashua did not permit observations to close the water or nitrogen budgets. Drainage flow and N concentrations were sampled from a single drain in the middle of each plot. Drains

Table 3
The 35 management systems studied at Nashua in the 1990–2003 period.

Crop rotation	Tillage system	N application method	N rate[a] (kg/ha)	Year(s)
Corn–corn	Chisel plow	Anhydrous	202	1990–1992
Corn–corn	Chisel plow	SM Fall and UAN Spring	184–201	1999
Corn–corn	Chisel plow	SM Fall	69–286	1993–1998
Corn–corn	Chisel plow	SM Fall on Corn and Soybean	200–220	2000
Corn–corn	Chisel plow	UAN Spring Preplant	131–138	1993–1998
Corn–soybean	Chisel plow	Anhydrous	168	1990–1993
Corn–soybean	Chisel plow	SM Fall and UAN Spring	168–173	2000–2003
Corn–soybean	Chisel plow	SM Fall	80–263	1994–2003
Corn––soybean	Chisel plow	SM Fall on Corn and Soybean	170–248	2001–2003
Corn–soybean	Chisel plow	UAN LSNT	150–186	1994–1999
Corn–soybean	Chisel plow	UAN Split LCD	168–178	2000–2003
Corn–soybean	Chisel plow	UAN Spring Preplant	110–168	1994–2003
Soybean–corn	Chisel plow	Anhydrous	168	1990–1992
Soybean–corn	Chisel plow	SM Fall and UAN Spring	167–265	2000–2003
Soybean–corn	Chisel plow	SM Fall	81–227	1993–2003
Soybean––corn	Chisel plow	SM Fall on Corn and Soybean	143–290	2001–2003
Soybean–corn	Chisel plow	SM Spring Preplant	206–215	1999–2000
Soybean–corn	Chisel plow	UAN LSNT	78–169	1993–2000
Soybean–corn	Chisel plow	UAN Split LCD	168–184	2001–2003
Soybean–corn	Chisel plow	UAN Spring Preplant	110–168	1993–2003
Corn–corn	Moldboard plow	Anhydrous	202	1990–1992
Corn–soybean	Moldboard plow	Anhydrous	168	1990–1992
Soybean–corn	Moldboard plow	Anhydrous	168	1990–1992
Corn–corn	No-till	Anhydrous	202	1990–1992
Corn–soybean	No-till	Anhydrous	168	1990–1993
Corn–soybean	No-till	SM Spring Preplant	122–235	2000–2003
Corn–soybean	No-till	UAN LSNT	141–204	1994–1998
Corn–soybean	No-till	UAN Spring Preplant	110	1994–1999
Soybean–corn	No-till	Anhydrous	168	1990–1992
Soybean–corn	No-till	SM Spring Preplant	127–209	2001–2003
Soybean–corn	No-till	UAN LSNT	142–206	1993–2000
Soybean–corn	No-till	UAN Spring Preplant	110	1993–1998
Corn–corn	Ridge till	Anhydrous	202	1990–1992
Corn–soybean	Ridge till	Anhydrous	168	1990–1992
Soybean–corn	Ridge till	Anhydrous	168	1990–1992

[a] The range of N rates applied only to corn (unless otherwise noted).

along the sides of each plot were installed to prevent plots from influencing their neighbors, but as those drains received input from both adjoining plots, neither flow nor N concentrations in these drains were sampled. Surface flow was not measured, although surface flow appeared to be small for most plots. N concentrations in plant biomass were sampled occasionally.

2.3. Simulation of management effects at Nashua (Steps 4 and 5)

Eight papers in a special issue of *Geoderma* entitled "Integrating Soil and Crop Research with System Models in the Midwest USA" (Vol. 140, No. 3) describe the physical and biological processes determining nitrogen loading and crop yields in Nashua. Looking forward, a key question is: Given that intensive monitoring and comprehensive simulation of agricultural systems for water quality is expensive, how can farmers across as large an area as possible apply the understanding gained from the research on tile-drained agriculture, and its response to management, to reduce nitrogen in tile flow while maintaining or enhancing economic returns?

2.3.1. Root Zone Water Quality Model (RZWQM)

> *No one believes a model save its developer. Everyone believes a data set except its collector.*

This aphorism, cited by the National Research Council (1998, p. 67), hints at the need for a more nuanced lending of credence toward both models and observed data. On the one hand, models are necessarily simplifications of very complex systems, with a suite of issues needing attention before one can have confidence in the results. Model developers feel more confidence in simulation results than do model users, perhaps because of genuine insight into the dominant processes being represented. On the other hand, many researchers would like to trust observed data and ignore the complexities needed to interpret all of the what-might-have-happened issues that concern field scientists.

With both a model and an observed dataset one can test the model against observed results, improve model calibration, and even improve model structure to better represent the processes being simulated. We used the Root Zone Water Quality Model, RZWQM, a comprehensive, state-of-the-science model designed to assess management impacts in the root zones of agricultural fields (Ahuja et al., 2000). RZWQM is a process-based, one dimensional model (vertical), with modules to assess six sets of physical processes: physical and hydrologic, plant growth, soil chemical, nutrient, pesticide and management processes. The nutrient module addresses both carbon and nitrogen cycles, but does not simulate phosphorus. The plant growth module simulates the crop, including root growth, as well as water, nitrogen and carbon uptake. By representing a plot's response to management by a single simulation, one is assuming that the plot is homogeneous across and down slope. The model has a sophisticated user interface to parameterize simulations and graphically present results. As a process-based model, RZWQM requires both a significant amount of information and a degree of expertise beyond what is needed for screening models. RZWQM has been thoroughly evaluated using data from numerous locations, conditions, and management, resulting in over 220 peer-reviewed publications, reports, or dissertations.

Weather data (solar radiation, daily rainfall) were derived from an on-site weather station for most of the years with missing data filled from nearby cities (Saseendran et al., 2007). Soil hydraulic conductivities and soil water retention curves were determined using soil samples collected in 2001 from a nearby field (Ma et al., 2007b). RZWQM was evaluated using long-term (1978–2003) field data for 30 out of 36 plots. We calibrated RZWQM using soil data from plot 25 and then used with the same soil and plant parameters, except for lateral hydraulic gradient, to simulate responses for the other 29 plots (Ma et al., 2007c). We used the generic crop growth component rather than the DSSAT option described in Saseendran et al. (2007). All recorded management operations were input into the model and used in the RZWQM calibration.

2.3.2. Review of prior RZWQM results at Nashua

Before applying a model to simulate a large, complex experiment, an empirical analysis can highlight important relationships in the observed dataset. Malone et al. (2007c) performed that analysis and developed regression equations that explained 87%, 85%, and 95% of the variation in soybean yield, corn yield, and nitrate loss in subsurface drainage. As might be expected, manure application can result in less nitrate leaching than UAN and spring application of N reduces nitrate leaching compared to fall application. The paper also points out that a metamodeling effort could provide an important complement to simulation modeling efforts over large areas by reducing the number of scenarios to consider while still providing quantitative estimates of management effects.

Malone et al. (2007a) enhanced the APSIM-DRAIN model (Keating et al., 2003) to support tile drainage simulation at Nashua. The enhanced model was used to simulate the effects of a winter wheat cover crop on N loading, and found a simulated reduction in loading of 38% compared to no cover crop. Bakhsh et al. (2007) used cluster and discriminant analysis to confirm that soil and topographic attributes affect corn and soybean yield patterns, which could be used to scale yield estimates from point scale models like RZWQM to field sizes much larger than the 0.4 ha plots at Nashua.

Ma et al. (2007a) reported that soil water retention curves from intact soil cores were taken near the long-term experimental fields at Nashua. The soil hydraulic properties saturated hydraulic conductivity and hydraulic gradient were estimated and used to calibrate RZWQM, resulting in improved simulations of water relations and N in tile flow compared to the default soil parameters. Sensitivity analysis showed that the yield and biomass were not sensitive to these hydraulic gradient properties.

Ma et al. (2007c) reported that lateral hydraulic gradients were calibrated for each plot to capture the difference in flow characteristics, so the tile flow, soil water storage and water table depth simulated values were similar to observed values. Crop yields, on the other hand, were over-predicted when UAN and anhydrous ammonia were applied, but under-predicted when fall swine manure was applied. Saseendran et al. (2007) used a hybrid RZWQM–DSSAT model and found the hybrid model did not result in better crop yield estimates than the generic crop component in RZWQM.

Ma (2007b) found RZWQM correctly simulated N concentration in drain flow increasing with tillage intensity and tillage intensity increased yearly drain flow and yearly N loss in drain flow. The model failed to simulate lower corn and soybean yields under no till compared with other tillage systems. Crop rotation effects on drain flow and concentrations were adequately simulated and the model simulated higher corn yields under corn–soybean systems than continuous corn. Although there were no observed data for comparison on controlled drainage effects, simulation indicated a 30% reduction in tileflow and 29% decrease in N losses and tileflow when using controlled drainage.

Malone et al. (2007b) used RZWQM to assess the effects of several N management strategies. In general, after calibration and thorough testing, RZWQM accurately responded to different N treatments. LSNT and split N applications, anhydrous ammonia, fall swine manure on corn, spring manure on corn, and fall swine manure application to corn and soybeans were all tested for their effects on yields and N in drain flow. Nitrate leaching from fall swine manure application, especially on soybeans, may have been over-predicted. Winter cover crops were also tested, although no observed data exist on winter cover crop effects at Nashua. The simulated N reduction with a winter cover crop was 31% compared to no cover crop at 150 kg N/ha, applied in the spring.

2.3.3. Parameterization of RZWQM for long term analysis

With a treatment cycle of 6 years, a 2-year crop rotation implies three observations of yields for each crop. Because of variable weather, observed crop yields and N loading associated with the treatments studied at Nashua are not directly comparable across experimental cycles. N loading observations began in the 1990–1992 period, and 1988 and 1989 were dry years having a residual effect caused as N build-up in the soil caused high N loading early in the 1990–1992 cycle. Similarly, in the second cycle, 1993 was a flood year, and hail damaged crops in 1995, so low yields for a crop grown in odd years of that cycle were the result of weather rather than treatment.

To reduce the effect of weather on N loading and crop yields, a number of treatments were simulated with the same 30-year climate input files (Table 4). A common climate input file from 1964 to 2003 was used, with the first 10 years of simulation considered a warm-up period, and treatments compared on the 30 years from 1974 to 2003. The simulated management systems fall into three categories: 12 systems similar to those studied at Nashua and in relatively common use in MLRA 104, designated as "Nashua Treatments"; a second series of 12 management systems expected to reduce N loading with lower N application rates applied in the spring with and without the cover crop conservation practice, designated as "Low Spring"; and six management systems that one would expect to have higher N losses, as more N is applied in the fall prior to a corn crop, designated as "High Fall".

2.3.4. Crop budgeting with DevTreks

The RZWQM model simulates corn and soybean yields. One cannot make an economic comparison of alternative management systems based solely on yields, as costs also vary, and both affect net returns. For example, even if yields decline under a no till management system, avoiding the expense of tillage operations could increase net returns, depending on output prices and the cost of fuel and herbicides. The only way to sort out such counterbalancing economic effects is to develop economic budgets for each management system.

The budgeting tool used in this study, EconDocs, has since been superceded by a new, web-based social budgeting tool called DevTreks (Boyle et al., in preparation). DevTreks implements the American Agricultural Economics Association recommendations for estimating agricultural costs and returns (AAEA Task Force, 2000), and includes extensive features for sharing, manipulating, and analyzing budgets.

We created crop operating budgets for all 504 crop years at Nashua between 1990 and 2003. Of those 504 budgets, only 420 correspond to the 30 plots simulated by RZWQM. All budgets were based on the equipment in use at Nashua in 2003, with national prices for most inputs in each year coming from National Agricultural Statistics Service (NASS, 2003). Expenses were calculated for operating costs, such as materials, fuel, and repairs, as well as allocated overhead costs, like machinery capital recovery costs. Net income was derived by subtracting operating and allocated overhead costs from total revenues (output yield ∗ output price). These budgets are similar to published budgets for Iowa, except the prices are

Table 4
The 30 management systems used in long-term simulations.

	#	Tillage	Rotation	N amount	N type	Season	Cover crop
Nashua Treatments	1	CP	CC	150	SM	Fall	No
	2	CP	CS	150	SM	Fall	No
	3	CP	SC	150	SM	Fall	No
	4	NT	CC	150	SM	Spring	No
	5	NT	CS	150	SM	Spring	No
	6	NT	SC	150	SM	Spring	No
	7	CP	CC	150	UAN	Spring	No
	8	CP	CS	150	UAN	Spring	No
	9	CP	SC	150	UAN	Spring	No
	10	NT	CC	150	UAN	Spring	No
	11	NT	CS	150	UAN	Spring	No
	12	NT	SC	150	UAN	Spring	No
Low spring	13	CP	CC	135	UAN	Spring	No
	14	CP	CC	135	UAN	Spring	Yes
	15	NT	CC	135	UAN	Spring	No
	16	NT	CC	135	UAN	Spring	Yes
	17	CP	CS	110	UAN	Spring	No
	18	CP	CS	110	UAN	Spring	Yes
	19	NT	CS	110	UAN	Spring	No
	20	NT	CS	110	UAN	Spring	Yes
	21	CP	SC	110	UAN	Spring	No
	22	CP	SC	110	UAN	Spring	Yes
	23	NT	SC	110	UAN	Spring	No
	24	NT	SC	110	UAN	Spring	Yes
High fall	25	CP	CC	200	Anhydrous	Fall	No
	26	NT	CC	200	Anhydrous	Fall	No
	27	CP	CS	168	Anhydrous	Fall	No
	28	NT	CS	168	Anhydrous	Fall	No
	29	CP	SC	168	Anhydrous	Fall	No
	30	NT	SC	168	Anhydrous	Fall	No

for different time periods, there is some variation in technology, and there was no charge for land (Iowa State University, 2006b).

Net returns were estimated for the 1974–2003 simulations by creating individual budgets for 1 year's corn and soybean crop under each management system. Long-term returns were calculated on the assumption that the same series of operations were repeated within each crop rotation for 30 years. Revenues were calculated as the crop yield for each year using the 2003 price for corn and soybeans. Costs for each crop year under each management system were derived from the DevTreks budgets and subtracted from revenues to calculate net returns.

The cost to implement a rye cover crop was estimated based on the planting and herbicide operations described in Kaspar et al. (2008, p. 130). The cost of using a cover crop practice was \$62.54/ha, with no cost share.

2.4. Decision support (Step 8)

We used the Facilitator decision support program, a generic multiobjective DSS which implements an algorithm described by Yakowitz and Weltz (1998) and applied to NRCS decision making in western Iowa described by Heilman et al. (2004). In this example with only two variables, net income and N loading, one could have used a more traditional economic tradeoff analysis, but for conservation planning a multiobjective tool that could easily handle additional decision variables, such as pesticide quantities or wildlife habitat evaluations, would be more flexible and appropriate for application by a Conservationist.

The goal in such a decision support tool is to select a number of issues to be addressed, identify decision variables reflecting progress toward addressing those issues, define several alternative courses of action, and quantify the effects of the management alternatives on the decision variables. We quantified the net returns for each of the 35 management systems shown in Table 3 by estimating net returns in DevTreks for both observed and RZWQM simulated yields. Observed and simulated net returns and N loading values were then entered into the Facilitator, and converted to scores in the range of 0–1.0 to reflect the effect of each alternative on each variable.

Weights for each variable are assigned to define the effect of each management practice on each variable to sum the variable into an overall desirability index. Because decision makers often have difficulty assigning specific weights to variables, Facilitator DSS permits decision makers to rank decision variables in order of importance rather than explicitly defining weights. The tool then calculates a best possible and a worst possible score consistent with the weights (and the requirement that the weights sum to 1.0) and the results are displayed graphically. The end result is not the identification of an optimal system, but rather a ranking of alternatives, from which the decision maker selects a system that best fits their equipment and skill set, and that improves upon the current system. For many issues the interests of stakeholders differ, which can be reflected in a different importance order of variables. Facilitator supports comparison of such differences.

A stylized decision example for Nashua illustrates the potential of the approach. In this case there are only two groups of decision makers: farmers and fishermen. The farmers are most interested in the economic benefits from crop production, and to a lesser extent are concerned with the N loading that causes downstream water quality problems. Conversely, fishermen in the Gulf affected by hypoxia are concerned with N loading and less concerned about the farmers' income. Two decision variables are defined, net returns and N loading, and linear score functions are established based on the range of values in the Nashua dataset. More N loading lowers the score in the range of 0–100 kg/ha, with the score function for net returns increasing as a linear function in the range of −100 to 500 \$/ha.

3. Results

3.1. RZWQM simulation of 1990–2003 Nashua dataset

N loading in tile drained systems is determined by the combination of tileflow and the N concentration in the tileflow. Fig. 4 shows the RZWQM simulation results compared to the measured crop yield, tileflow, N concentration, and N load for 30 plots over 14 years totaling 420 plot years. There is significant scatter around the 1–1 line for corn yields, in part because of processes affecting yield, e.g., insects and hail. Another issue was an increasing area-wide trend in corn yields across the 14 years. A regression of yields in Chickasaw county for the period 1990–2003 using data from the National Agricultural Statistics Service (NASS, 2010) indicates a 3% annual increase in corn yields and a 1% increase in soybean yields. Parameterization of RZWQM assumed that crop properties affecting yield were constant throughout this period for both crops.

3.2. Economic analysis of 1990–2003 Nashua dataset

Fig. 5 shows the 420 measured and simulated crop yields against N loading as well as net returns compared to N loading for each plot year. The r^2 value for the annual simulated N loading values compared to the observed is 0.6 and the root mean squared error (RMSE) is 16.8 kg/ha. Averaging the annual values into the 35 management systems increases the r^2 value to 0.68 and decreases the RMSE to 12.0 kg/ha. The corresponding r^2 value for the annual net return simulation is 0.58 with an RMSE of 126 $/ha. Averaging the annual net returns for the 35 management systems increases the r^2 value to 0.66 and decreases the RMSE to 65.9 $/ha.

The combined RZWQM and DevTreks results for the 35 observed management systems are shown in Fig. 6. The measured results are shown in open circles connected by a line segment to the corresponding simulated result in a closed circle. The greater the length of the line segment the greater the difference in crop yield or N loading, though the number of years and plots for each system is not equal.

3.3. Decision support for Nashua dataset

Measured values of N loading and net returns were entered into the Facilitator for all 35 management systems and the alternatives were ranked using the Farmer's and Fishermen's priorities described in Section 2.4. The same process was also followed using simulated values of N loading and net returns. The average of the highest and lowest possible scores was considered representative of the overall score for each system. The simulated and observed results using both importance orders are shown in Fig. 7. The r^2 for both importance orders is 0.68 and the RMSE for both is less than 0.1. Selecting a management system from among those simulated systems with the highest overall scores would, in almost all cases, also lead to the selection of a management system with a high score based on observed results. In the cases where the rankings are not equal, the difference in overall score is small. Table 5 summarizes the ranks of management systems selected using simulated results that were also highly ranked based on observed data.

To resolve N contamination issues from agriculture, the critical issue is to help farmers voluntarily move from a system selected for a high expected net return with little to no weight on N loading to a production system that weights N loading, perhaps with financial support of a conservation program. In framing the decision, one has to make a number of assumptions to quantify management effects, such as that the future climate when the management system is implemented will be similar to the recent climate (or the simulation model's climate inputs); that prices will remain constant at levels near those used to calculate net returns; that farm programs will not change drastically; and that new technology will not appear to drastically change the range of options facing the producer. As noted above, additional assumptions are needed to rank alternatives.

3.4. Long term tradeoffs

A total of 30 long term management systems were defined and simulated for the 1974–2003 year period, and budgets estimated. We assume that RZWQM accurately simulates all outputs under

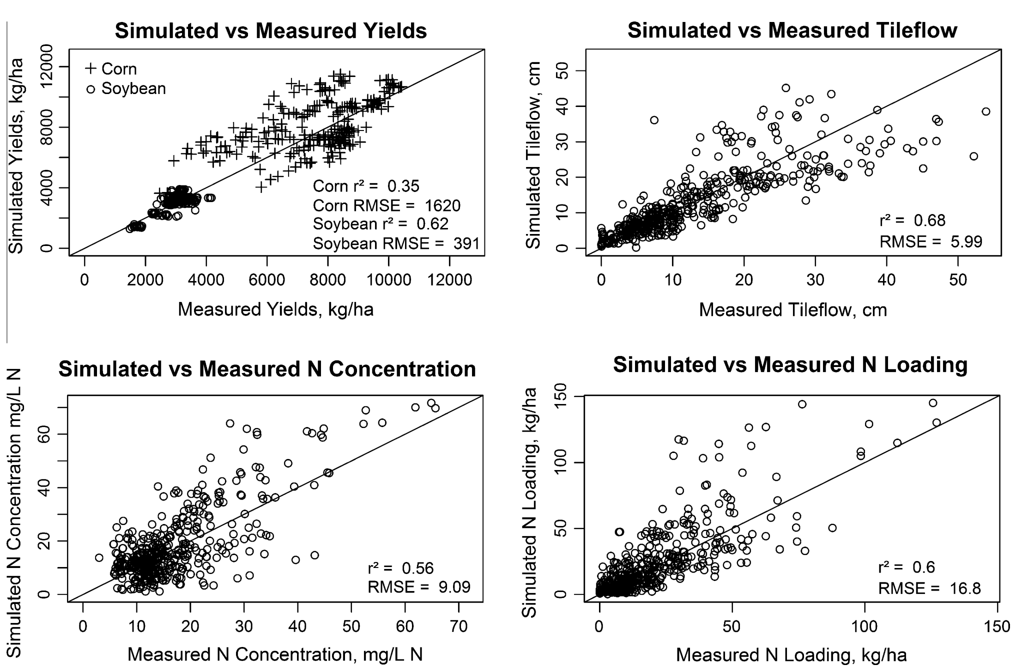

Fig. 4. Comparison of measured crop yield and N loading for the same management systems in the same years across plots, and simulated vs. measured crop yield and N loading.

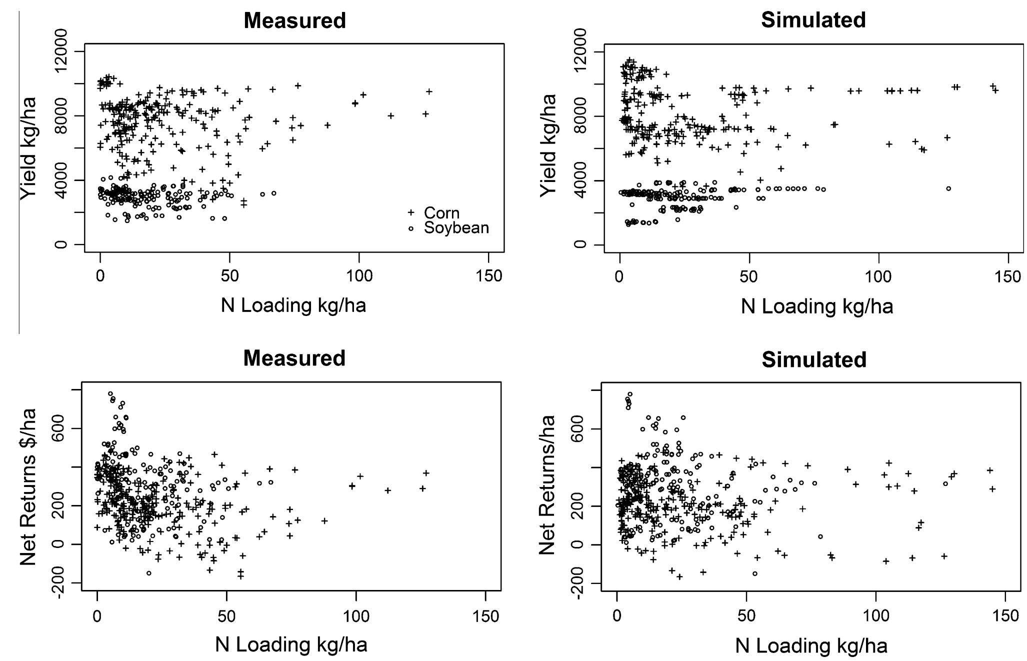

Fig. 5. Plot of annual values and management system averages of RZWQM simulated crop yields and N loadings.

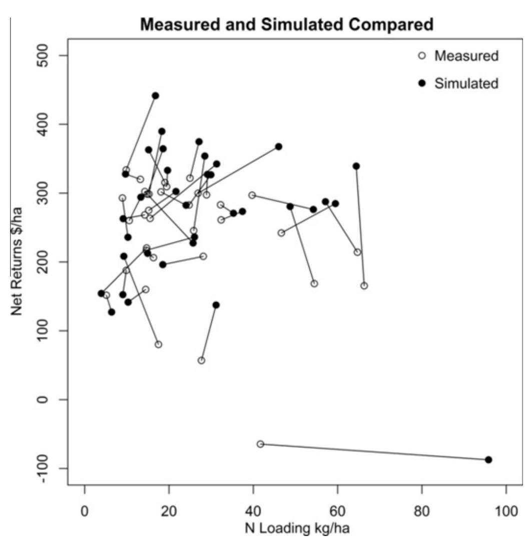

Fig. 6. Plot of measured and simulated net returns and N loadings for the 35 systems studied at Nashua from 1990 to 2003.

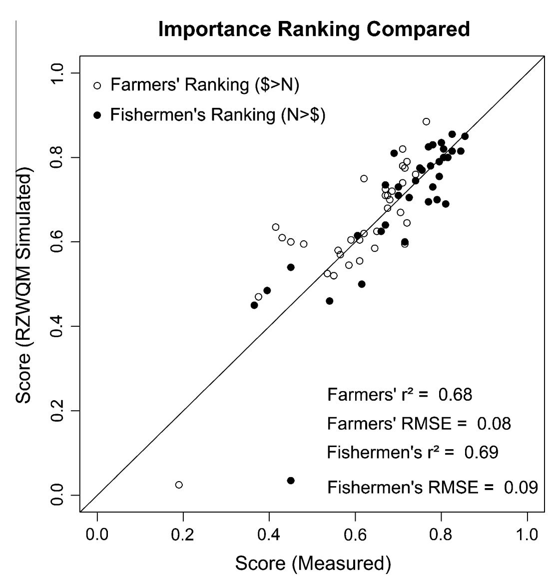

Fig. 7. Plot comparing overall scores for 35 1990–2003 management systems using observed and simulated values of N loading and Net Returns.

all management systems. In the process outlined in Fig. 2, the expert review could require modifications to a simulation model or restrictions on its application. The long term average N loading and net returns are plotted for comparison in Fig. 8. The most desirable systems have both high net returns and low N loadings. If a farmer agreed with the assumptions embodied in Fig. 8, then a production possibilities frontier of the most desirable systems, with the highest returns for a given amount of N loading, could be identified.

A more robust analysis however, could look at the expected effects of management subsystems, recognizing that the effect of any subsystem is defined by its overall context. In Fig. 9 the crop rotation and tillage system of all 30 systems is identified. Two corn–corn systems had extremely high N loading rates, but the others were roughly the same as the corn–soybean and soybean–corn systems. The profitability of each rotation will depend on the ratio of corn to soybean prices. This analysis used the 2003 prices of $2.42/bu for corn and $7.34/bu for soybeans (NASS, 2010). For these prices, the corn–corn rotation was decidedly less profitable than the corn–soybean and soybean–corn rotations. As crop prices are notoriously volatile, corn–corn rotations may have become more profitable. Since 2003 the price of corn has increased, and as noted earlier, yield increases for corn are rising faster than for soybeans. One would want to re-run this analysis with the decision maker varying prices over their planning horizon.

Net returns were higher for the no till systems than for the chisel plow. Ma et al. (2007b) found that RZWQM did not capture an observed decline in corn yields under no till, although Martens (2001) in a survey article reported varying effects of no till on yields relative to conventional tillage treatments. RZWQM also does not simulate any potential soil quality improvements, such

Table 5
Number of simulated management systems that are also ranked at the top of the Facilitator ordering when using observed data.

	Farmer's preference ($ > N)	Fishermen's preference (N > $)
Top alternative	1	0
Top 5 alternatives	3	2
Top 10 alternatives	7	8
Top 20 alternatives	18	17

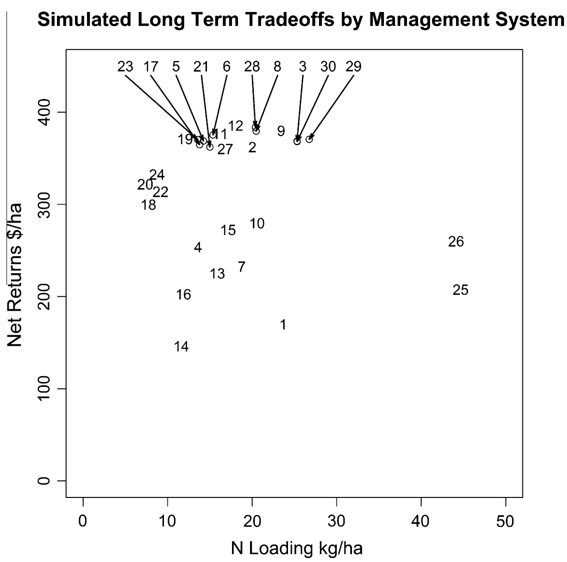

Fig. 8. Plot of annual average net returns and N loadings based on RZWQM simulations and DevTreks budgets for 1974–2003.

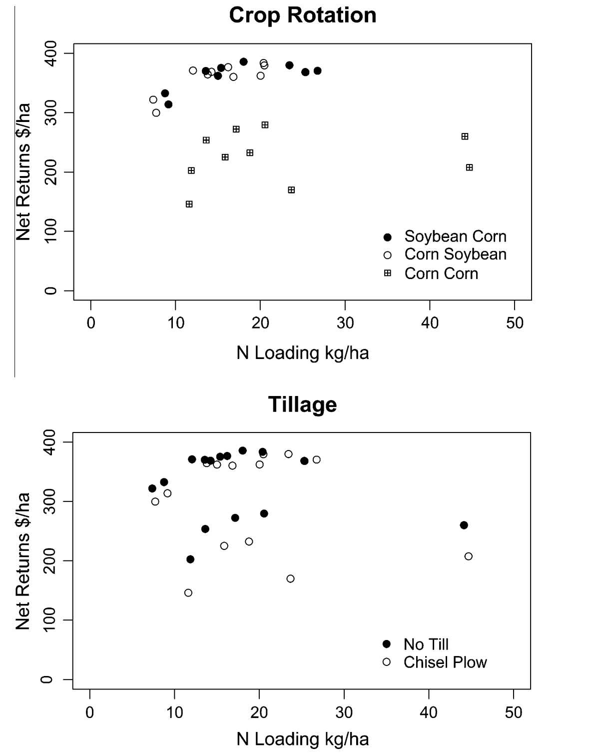

Fig. 9. Plot of annual values and management system average net returns based on RZWQM simulated crop yields and N loadings for 1974–2003.

as for aggregate stability, resulting from long term application of no till.

An even more detailed picture of the effects of management on net returns and N loading is derived from considering the effects of different N application methods, timing, amounts, and the effect of a cover crop (Fig. 10). All three methods of N application; UAN, swine manure, and anhydrous ammonia, consistently produce high net returns. Anhydrous ammonia use appears to lead to higher N loading, although it was only applied in the fall. The fall swine manure application may overestimate N loading (Malone et al., 2007b). N application rates affect both N loading and income. Simulations with the lowest N application rate, 110 kg/ha, resulted in yields leading to net incomes close to highest in the study. Application rates in the range of 135–168 kg/ha appeared to define a net return frontier, although variations in other management subsystems can cause a variation in N loading of a factor of 2. The highest rate, 200 kg/ha was only applied in the fall on continuous corn, which reduced its net return and caused very high N loading. As would be expected, systems with cover crops had the lowest N loading, but with lower net returns.

4. Discussion

4.1. Simulation, review, and application of the Nashua dataset

The parameterization, calibration, and analysis of RZWQM for the Nashua dataset required several scientist-years, far beyond the skills and time available to conservationists working with farmers. In addition, modification of RZWQM was needed to incorporate lateral flow. Clearly this step in the overall process should be performed by modeling specialists. Table 6 summarizes the efforts made to systematically simulate and review management effects at Nashua and incorporate this information into decisions for RZWQM.

4.2. Related N management efforts

The current NRCS database of management system is called Conservation System Guides (CSGs). Although the quality of CSGs is quite variable both within and between states, the general format of an individual CSG is consistent. On croplands a CSG is defined for a soil within an MLRA in a state, though not for all soil series. The CSG describes the management systems and resource problems commonly found (baseline condition), and either qualitative or quantitative estimates of the effects of conservation practices on the most salient resource problems. It is perhaps more appropriate to think of CSGs as a knowledge base and training tool than as an integrated component of a decision support tool. CSGs do provide an expandable framework to form a database of management system effects from simulation models.

Regional efforts to address the general issue of reducing N loading have focused on the economics of N application (Iowa State University, 2006a). For example, Agronomy Extension of Iowa State University has a website with a Corn Nitrogen Rate Calculator (Iowa State University, 2010) that calculates the Maximum Return to N, a value that maximizes net returns to corn within a state or region given a rotation, N cost, and corn price. The range of N application rates resulting in a return to N within a dollar/acre of the maximum is calculated based on a dataset of reported N application rates and yields. Decision support focusing on setting N application rates based on net returns is clearly an important first step in reducing N loading. However, the optimal N application rate considering only the farmer's net returns will not be optimal in terms of economic efficiency if the crop production causes downstream damages.

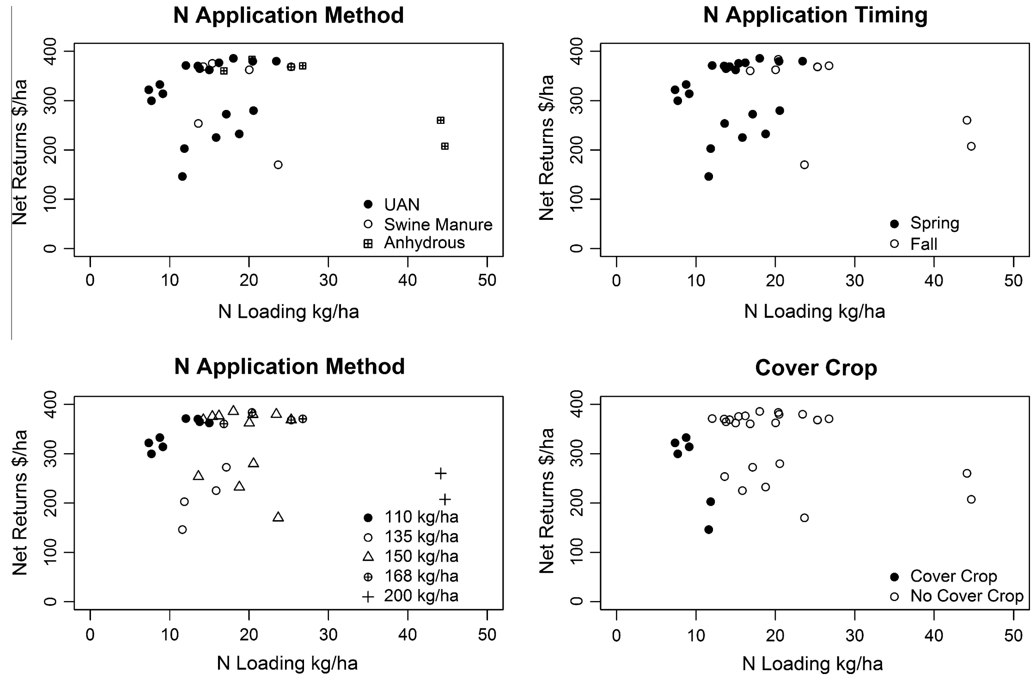

Fig. 10. Plot of tradeoffs by management subsystems for 1974–2003 simulations.

Table 6
Actions required to apply Nashua dataset to its representative area (MLRA 104.1).

Step in quantifying effect for database (from Fig. 2)	Issues in application to Nashua dataset	Resolution in Nashua study
1. Define resource problems	Nitrogen considered a problem in water bodies from Iowa to Gulf of Mexico	N in tileflow is a problem due to "short-circuit" effect
2. Define a set of management alternatives that might address the identified problems	Extensive dataset on crop production, tillage, and N application methods and timing. Some conservation practices had not been tried	Review effect of cover crops from field research at other locations
3. Assess dataset from study area	Moldboard plow and ridge till are not widely used in area. Not all systems were able to be implemented coincident with the 6 year cycle. Soil differences apparent in some plots. Closed water and nitrogen budgets not available	Moldboard plow and ridge till systems no longer considered candidate solutions. For comparison purposes, some N management systems in a cycle were studied for less than 6 years. Simulate 30 out of 36 plots for 1990–2003
4. Simulate management alternatives in the resource setting	RZWQM did not consider all processes needed for simulation of crop yields and N loading at Nashua. Machinery used on Nashua research farm smaller than for commercial farms	Improvement to RZWQM: consideration of lateral flow. DevTreks used the Nashua machinery in economic calculations
5. Expert review for study area	Crop yield information is available at the county level, but no other nearby observations of N in tile flow with similar management systems in place	Eight papers on Nashua dataset peer reviewed prior to publication in a special issue. The long term simulations have not been reviewed except by the authors
8. Apply quantified information on management effects within a decision support framework	Nashua is an experimental farm and does not make decisions on the same basis as commercial farming operations	Example DSS application performed for Nashua farm, broader regional application not implemented yet

4.3. Scaling up to a regional database of management effects

Although the effort described here for MLRA 104.1 did not implement Steps 6 through 9 to populate and utilize a management effects database for decision-making, our experience identifies the effort needed to scale from a research site to an MLRA. Step 6, to simulate management systems would be quite demanding, essentially requiring the integration and documentation of all available information on management system effects across the MLRA. The expert panel (Step 7) would have a very demanding task in reviewing a MLRA-wide database, especially to address ancillary datasets, new management systems, and uncertainty. Applying the dataset in Step 8 should be done through a decision support tool integrating information on incentives from conservation programs together with the technical relationships relating management to N loading. Lastly, new soil, slope, management system combinations would be simulated on an as-needed basis. The complexity of this approach requires an integrated effort as described below.

First of all, such a scaling effort requires significant leadership. Expertise is needed in numerous areas and requires a team approach, where a leader could articulate the overall goals, find resources as needed, and make the project interesting enough to produce an expert reviewed database of management system effects. Action agencies like the NRCS would need significant upper management support to enable a sustained effort without redirection to new agency initiatives. Scientists could be attracted to an intellectually interesting effort, with an opportunity to point to their individual contribution toward improving the science used to manage natural resources, but the demands on their time must be limited.

Second, it would be critical to design an approach for populating and reviewing the database to derive the greatest value from commonly used management systems on the widely distributed soils without evaluating all possibilities. A modeling specialist could extend the parameterizations to new situations in Step 9 as the need arises. Metamodeling could be an important complement to the application of a comprehensive simulation model, especially for continuous variables that would require many simulations, like N application amounts, as shown by Malone et al. (2007c).

Third, creating a database would require an investment in customizing information technologies to manage the data flow. Tools to store and manipulate the data, version control of input files, automation of pre- and post-processing, and tools to reduce voluminous model output into graphical displays would facilitate the creation of a quality assured database. Most important would be tools to help the team collaborate without an overwhelming burden of meetings.

4.4. Long term improvement of a management effects database

To those with a scientific view, if the weight of evidence in support of previously quantified management effects changes, then one should change one's view about the expected effect of management. In practice however, it is difficult for agencies that deal with the public to change their underlying science, especially if conservation program spending is involved. Populating a database of management effects across a large area would be a significant effort, and a revision might only be justified on a periodic basis.

If a particular algorithm does not adequately represent a physical or chemical process, and another model builder thinks that their process representation is an improvement, they would want to show the advantages of their representation, particularly if the input parameters could be documented in a model-independent markup language so that modeling comparisons could be performed inexpensively. Similarly, if an experimentalist finds results that indicate differences or changes over time, there would be a mechanism to compare the new results with the old. Such a transparent approach to documenting the science could lead to conflicting claims and challenges in the short and medium term, but in the long run would result in much better understanding of management effects.

The last point to make about the benefits of a database of management effects is that in addition to supporting decision making at the field scale, it would permit a much more robust effort for policy analysis. One could quantify the conservation that taxpayers are buying with investments in conservation programs, and improve those programs by identifying the most effective practices. Systematic comparisons of onsite costs to manage N loading could be made with the cost of mitigating N within the local watershed through practices such as constructed wetlands. Quantification of onsite costs would also help with the comparison of downstream costs in local water bodies as well as costs imposed by hypoxia in the Gulf.

5. Conclusion

We used the RZWQM simulation model and DevTreks budgeting tool to quantify the effects of management systems on farm income and N loading. Two sets of simulations were performed, first for 35 systems through the observed 14 year study period and second for a set of 30 systems over 30 years. We compared the ranking of management systems based on observed data and simulations from RZWQM in the Facilitator multiobjective tool, and found that calibrated RZWQM results led to a very similar ranking compared to observed results, from both an onsite and offsite perspective. The analysis was specific to the Nashua experimental site and the prices and time periods involved. We describe, but do not implement, an approach to systematically extending the analysis to the larger area that Nashua represents. The most promising path to knowledge about difficult natural resource issues like N loading in tileflow will combine all elements of science to quantify management effects with the recognition that there are very real limits to human knowledge in such matters.

The approach proposed here of systematically populating and quality assuring a database of management system effects requires a substantial investment and presupposes the ability of the research and conservation community to collaborate effectively. In many parts of the country an effort to digest and synthesize research results into simple guidelines or decision rules may be appropriate. In other parts, either a single simulation model or a combination of models and qualitative tools would be appropriate. However, there will be areas where a more sophisticated approach is required. Managing N in tile drained agriculture inside the Mississippi Basin is a candidate for a more systematic approach to quantifying management effects. Indications of that fact include: large negative offsite effects like hypoxia in the Gulf of Mexico, the inability to develop an intuitive understanding of N loading based on visual evidence, a lack of accepted tools for N management in tile drained agriculture, and the critical impact management and physical factors have on the "short-circuiting" of N into tileflow.

Einstein's famous suggestion to make things a simple as possible, but not simpler, implies some level of detail in process representation in natural resource simulation models. Because farmers implement management systems on a field basis, ultimately quantification of management system effects also has to be done at that scale. Quantification of management effects at the field scale requires a physically based model that represents the effect of management on natural processes. The use of a physically based, rather than a screening, model requires a significant parameterization and calibration effort. A rich dataset like Nashua that describes measured effects of management on crop yields, tileflow, N concentrations, and other aspects of the water and N budget can support model calibration. Parameterization and calibration of comprehensive physically based models requires a dedicated modeling specialist. Similarly, another specialist, an economist, is needed to convert crop yields into crop budgets.

In extending results to a larger area, both the simulation and economic experts could benefit from a quality assurance review by a team of experts familiar with the agronomic and water quality issues, physical processes, ancillary datasets, and local monitoring networks. The resulting quality assured database could be used in a decision support framework to promote the adoption of management systems that maintain incomes while improving water quality, as well as for policy analysis. Lastly, an adaptive approach should be used with the quantitative dataset so that management systems that reduce N loading are implemented, and concentrations of N in water bodies monitored, with additional steps taken until N concentrations in the stream system reach a level deemed acceptable.

Acknowledgements

We would like to thank Carl Pederson and Ken Pecinovsky of Iowa State University, Cathy Woodard and Caitlin Hall of the University of Arizona, Jim Ayen, Alan Lauver, Barbara Stewart, Michael Sucik, Steve Brinkman, and Hal Cosby of the NRCS in Iowa, Reggie Voss, formerly of the Extension Service, Philip Algreen of Agri Drain, Terry Meade, Bob Jacquis, and Gerardo Armendariz of the Agricultural Research Service.

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