Nitrogen Mass Balance Report: Simulation Modelling Results of Potato Crop Management at Becker.
Managing Agricultural Environments of North-Central Sandy Soils: Research Objective E.4
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INTRODUCTION

This report contains the simulation modelling estimates of the impacts from nitrogen management practices at the Becker K&O Sap test-site during the 1994 crop season. The research objective was to assist the grower better manage his nitrogen resources by supplying him with real-time computer analysis of field nitrogen conditions. Of particular concern was the potential for nitrate leaching past the plant root zone. The nitrogen mass balance, an accounting of all nitrogen sources in the system from the start of the growing season to the end, is the primary focus of this report. Modelling a complex agricultural system requires the acceptance of a great number of simplifications and best-guess assumptions. A brief and partial description of some important model assumptions are outlined in the first section of this report. The second section details the results of the 1994 season in terms of the nitrogen mass balance. In summary, as much as 47-percent of the grower supplied nitrogen leached past the plant root zone and was lost to the water table. The model also detected a period of nitrogen stress during the growing season, which ultimately resulted in an estimated yield loss of about 2-percent. Finally, section 3 examines how the nitrogen mass balance would change if the grower's irrigation schedule were reduced by half, and credits were taken for nitrates in the irrigation water.

SECTION 1> Details of the Modelling Assumptions.

The Simulation Model

Estimates of the nitrogen mass balance were made using a computer simulation program called NCSWAP. This model combines climate data with crop management decisions to study their impact on the soil, water, and plant systems. Nitrogen levels in these various components may rise or fall over the growing season, based largely on the assumptions made about their individual characteristics. Hence, it is important for an understanding of the model's findings that a number of these significant assumptions first be examined. The rest of this section, therefore, describes the soil profile and its hydraulic characteristics, assumptions about chemical and biological transformations, and factors affecting crop development. The simulation period starts on April 11th --the day before planting-- and ends with harvest on September 11th (153 days).

The Soil Profile:

The Becker site is located on the Anoka sand plain, and consists primarily of a loam-sandy soil, generically known as a Hubbard. Field samples were taken to define horizons within the soil profile which share homogeneous soil properties. For this simulation the profile geometry includes 5 horizons (table 1). These horizons are arranged in a series of depths from the surface to 120 cm (or about 4 feet). Each horizon is further divided into 6 cm. segments, for a total of 20 segments. While the choices of horizon depths are somewhat arbitrary, they also reflect other real considerations. The third horizon for instance is something of a "plowpan", representing conditions of repeated compaction; mechanical and other. The 120 cm. profile bottom is nearly equivalent to the depth of the suction tubes used to measure soil water nitrate concentrations in a related field experiment.

Table 1 ----- Initial Physical Properties by Soil Horizon ------

HORIZON #	DEPTH (cm.)	TEXTURE	BULK DENSITY (gm/cm3)
1	0-6	Loam Sand	1.54
2	6-36	Loam Sand	1.60
3	36-48	Loam Sand	1.62
4	48-72	Loam Sand	1.65
5	72-120	Sand	1.66

Each horizon is assigned a value for the soils bulk density. This number is a measure of the mass or weight of a unit volume of dry soil; including both solids and pores. Bulk density increases in value with depth -- as an expression of compactness. Despite the profile's relatively high bulk density, and the existence of the plowpan layer, the sandy nature of the Becker soil makes for moderately- to excessively-well drained soil conditions.

The surface horizon, in particular the top segment, plays an important part in the simulation process. For simplicity, the surface is assumed to be 100 percent bare. No reduction in evaporation occurs due to residue, and only the first segment (top 6cm) contributes to evaporation. Tillage events are considered by the model, and they have an impact on the bulk densities of the segments affected. The bulk density of the top segment is also affected by the impact of rain and irrigation events. Over time, however, the soil segments return to the bulk density table values.

The Hydraulic Profile:

A second set of assumptions must be assigned for the hydraulic properties of each horizon (Table 2). The initial gravimetric water content of the profile is set to a near field capacity condition, as determined by field observation. The field soil water content at water stress, saturation and field capacity, are further described both in terms of gravimetric and volumetric measures. These two measures relate similar information about the profile water content. Gravimetric measures indicate the amount of water per gram of soil or mass, while volumetric measures represent the amount of water per volume of soil. Both are related to bulk density, and reflect the inter-related nature of water movement through the soil profile.

Table 2 Initial Hydraulic Properties Per Horizon -- Water Content

Horizon	Initial Content (ml/gm)	@ Water Stress Gravimetric (ml/gm)	Volume (ml/cm3)	@ Saturation Gravimetric (ml/gm)	Volume (ml/cm3)	@ Water Fld Cap. Gravimetric (ml/gm)	Volume (ml/cm3)	% Saturation
1	0.139	0.037	0.057	0.270	0.416	0.149	0.229	55.00
2	0.128	0.036	0.058	0.250	0.400	0.138	0.220	55.00
3	0.122	0.030	0.049	0.240	0.389	0.132	0.214	55.00
4	0.117	0.020	0.033	0.230	0.380	0.127	0.209	55.00
5	0.111	0.100	0.166	0.220	0.365	0.121	0.201	55.00

Rain and irrigation add moisture to the hydraulic profile dynamics over the growing season. NCSWAP equilibrates soil water back to field capacity in 2 days for light soils like the Becker Hubbard, and in 3-5 days for heavier soils. The redistributive flow is only in a downward direction; no upward capillary suction is assumed to occur. With the exception of the third horizon "plowpan", saturated hydraulic conductivity is high and does not limit flow. While the model is capable of impeding water movement through the lower boundary of the profile, the lower bound in this analysis is open to drainage.

NCSWAP is sensitive to plant stress from inadequate moisture, and crop development begins to suffer when segments in the root zone fall below their water stress levels. The model does not, however, impede plant development when profile water content values exceed the water saturation limits. When rain or irrigation events occur, the computational time-step for soil biological transformations and infiltration processes is 5 times a day; otherwise it is once a day. Root and crop top growth are always computed once a day. During the 1994 season, steady rains and ample irrigation held field soil water conditions at or near field capacity -- according to both field observation and model estimate.

Chemical and Biological Transformations:

The next set of assumptions create the framework for the chemical and biological processes that drive seasonal changes in the active organic pool of nitrogen (table 3). This pool is an important "natural" source of plant nitrogen, and includes the microbial mass (Pool I) and nutrient humus (Pool II). Activity within the microbial mass is affected by factors such as, the amount of residue, water content, temperature, and the availability of nitrogen in the soil profile. Pool I activity supplies or depletes the level of plant available nitrogen stored in the nutrient humus of pool II. If over time the humus nitrogen degradation is greater than the nutrient replenishment, the soil fertility will go down. Conversely, this humus degradation also represents nourishment for the growing crop.

Table 3 assigns a carbon content and C:N ratio to each horizon. The initial size of the active organic pool in the total 120 cm. profile was estimated at 215 kg/ha, while the initial level of inorganic nitrogen in the profile was set at 30 kg/ha. The stable humus (Pool III), much as the name suggests is stable, and was held constant throughout this analysis. Notice that only the first two horizons of the profile had measurable levels of nutrient materials.

Table 3 ------- Initial Chemical and Biochemical Properties per Horizon -------

HORIZON	TOTAL NH4	NO3	UREA	POOL 0+I + NIT (MICROBIAL MASS)		POOL II (NUTRIENT HUMUS)		POOL III (STABLEHUMUS)	
	PPM N	PPM N	PPM N	PPM C	C/N	PPM C	C/N	PPM C	C/N
1	0.7	1.9	0.0	70.0	10.0	1000.0	20.0	0.0	20.0
2	0.7	1.9	0.0	30.0	10.0	500.0	20.0	0.0	20.0
3	0.4	1.4	0.0	0.0	10.0	0.0	20.0	0.0	20.0
4	0.5	1.1	0.0	0.0	10.0	0.0	20.0	0.0	20.0
5	0.2	0.5	0.0	0.0	10.0	0.0	20.0	0.0	20.0

Several other nitrogen related factors are worth noting briefly as well. Nitrification rates govern the transformation of ammonium to nitrates, and differ in the first 2 horizons from the rest of the profile. From the surface to 36 cm. the nitrification rate is 15 ppm/day, while below that level it falls to 5 ppm/day. The ratio of soluble to total NH4 was set at 0.2 for the first 2 horizons, and at 0.5 for the remaining 3 horizons. The process transforming ammonium to nitrate (nitrification) is affected by soil temperature and soil water content levels; specifically where saturation conditions occur. At near-saturation levels, nitrification is replaced by denitrification. Denitrification is the process by which nitrogen (nitrate) is biologically converted to gaseous nitrogen, which is subject to atmospheric losses. Finally, the downward flow of soluble (inorganic) nitrogen is set at 65-percent that of the water flow.

Reference Crop Details.

An important feature of NCSWAP is the use of a reference crop in defining the simulated crop development. The simulated crop can at best achieve the yield potential of the reference crop, but can not surpass it. The reference crop for this simulation is a potato crop grown in 1991 at the Becker experiment station. No water or nitrogen stress was observed during the 1991 crop development. The effects of air temperature on crop development is computed in terms of degree day accumulation. The model calculates degree days from high and low daily temperature inputs. Plant population was set at 39,500 plants per hectare in keeping with the actions of the grower, and it is assumed that the population remains constant until harvest.

Many other model assumptions are set by the programmer at the start of the season. Of these, the most important crop assumptions are the maximum potential yield and final crop nitrogen content. The maximum potential yield was set at 14,600 kg/ha (dry mass) for total top mass and tuber growth. The final crop nitrogen concentration was assumed to be 1.5 percent. Based on these factors, the maximum potential crop nitrogen uptake was 226 kg/ha. Root mass assumptions are equally important to crop development and nitrogen use. Root penetration occurs at 1 cm./day for the first 36 days, and 0.35 cm./day until 80 days past emergence. Like the above ground crop mass, roots are assumed to be uniformly distributed over the field. Hence, the model can not distinguish between conditions in the furrow and the row.

Rainfall and Irrigation:

Rainfall during the simulation period (April 11 -- Sept. 11) was 60 cm., occurring in 39 events. In addition, the grower added 45 cm. of irrigation water. Nitrate contamination of irrigation wells is a recognized problem on the Anoka sand plain. Typically wells have nitrate concentrations ranging from detectable levels (0.5 ppm) to as high as 40 ppm. Nitrate concentration levels were measured (twice) at 22 ppm from the field site pivot, and this was the level used in simulation. Hence, the irrigator alone is estimated to have contributed 110 kg/ha of nitrogen (nitrate) to the system.

Grower-Supplied Nitrogen Management:

The grower applied nitrogen (N) at a rate of 290 kg/ha over 4 applications. The crop received a starter application of 35 kg/ha on April 12th. Emergence was half complete on May 15. The second (emergence) application was 85 kg/ha on May 21; air delivery, broadcast over the row and cultivated in. The third (hilling) application was 135 kg/ha on May 30; again air delivery, broadcast over the row and cultivated in. As the crop was reaching full development, the fourth and final treatment of 45 kg/ha was applied through the irrigator on July 13th. The crop was killed Sept. 1, and harvested 10 days later. Soil water remained at field capacity all season.

SECTION 2> Simulation Modelling Results -- Nitrogen Mass Balance: Becker Potatoes 1994.

The principle topic of this report is the change in soil-water-plant nitrogen levels over the 1994 growing season for potatoes at Becker. Table 4 summarizes the initial and final values for various components of the nitrogen system. At the center of activity is the crop, which had a total seasonal demand of 220 kg/ha nitrogen. This was only slightly below the reference crop maximum potential N uptake of 226 kg/ha.

On the right side of the table are estimates of initial and final nitrogen conditions in the active organic pool and inorganic profile. The active organic pool fell from 215 kg/ha to 115 kg/ha over the period, while the amount of inorganic N in the profile finished higher, at 45 kg/ha. Combined with the inadvertent addition of 110 kg/ha from the contaminated irrigation well, the total background N contribution totaled 355 kg/ha over the season. The model estimated total crop uptake from these background resources at 95 kg/ha, or 43 percent of the total crop need. Denitrification from background sources was estimated at 20 kg/ha, leaving a 80 kg/ha seasonal leachate total.

Grower-supplied nitrogen totaled 290 kg/ha over the growing season (table left). The crop's remaining N needs (57 percent or 125 kg/ha) were met by the grower-supplied N. Yet, only 43 percent of the grower supplied N was used by the crop. Another 10 percent was lost in small portions to denitrification, root and plant residuals, and the active organic pool. The remaining 47 percent (140 kg/ha) leached past the 120 cm. horizon -- presumably headed for the irrigator wellhead. Add to this amount the 80 kg/ha recycled from background sources, and the total seasonal nitrogen leachate equaled 220 kg/ha. A larger number than most researchers have previously reported.

Paradoxically, the crop experienced nitrogen stress despite the (periodic) over abundance of nitrogen. This clearly demonstrates the opportunity for better management of the rates and timing of nitrogen applications, actions which could both improve yield and reduce nitrate leaching.

Table 4. -- Summary of the nitrogen mass balance. (Kg/Ha)

Total System Nitrogen Resources		
Grower-supplied N 290	Background nitrogen sources	355
	- initial active organic	215
	- initial inorganic profile	30
	- seasonal irrigation	110
Total Crop Nitrogen Uptake <220>		
Grower-supplied Crop N <125>	Background Crop N <95>	
Post-harvest Nitrogen Conditions		
Grower-supplied nitrogen	Background N sources	
- residual top mass <0>	- final active organic <115>	
- residual root <15>	- final Inorganic profile <45>	
- denitrification <10>	- denitrification <20>	
Total Nitrogen Leached @ 120 cm.		
Leachate <140>	Leachate <80>	

Model Validation -- Can these numbers be right ?

While point estimates provide valuable information, the nitrogen balance framework outlined above holds the most potential for further analysis. Since the model can simulate individual elements of the nitrogen system separately, and can detail a range of variables, the researcher can manipulate each field assumption and isolate its impact on the overall system. Climate and management decision alternatives may be tested as well. The question to ask yourself in judging the nitrogen balance of table 4, is whether (individually and as a system) the numbers can be deemed "reasonable". Many arguable adjustments could be made to the final N distributions of table 4., but significant total nitrate leaching is difficult to assume away -- even with the most optimistic model adjustments. There are few affordable ways to test the accuracy of agricultural models like NCSWAP. Two independent measures were taken from data collected by colleagues working the same site. First, suction tube water nitrate concentration readings are compared with the model generated estimates. The second validation of model accuracy is based on empirical and anecdotal evidence gathered over the growing season, in particular during a period of crop nitrogen stress.

1. Comparing soil water N concentrations.

One independent check of model accuracy is whether soil-water nitrate concentrations collected in the field can be predicted in simulation. Suction tube data were collected for between-row, within-row, and paratil treatments; four samples were gathered weekly for each treatment. NCSWAP doesn't make such fine distinctions as furrow and row, but it can estimate nitrate concentrations on a daily basis. Graph 1 shows the concentration levels (ppm) of soil water as it leached past the 120 cm. mark. The solid line represents the simulated nitrate concentration levels. The triangular figures mark the measured readings of one individual suction tube -- WB4. Solid square figures mark the average reading for all between-row measurements, including WB4. As self-serving as it may seem, we choose to compare simulated nitrate levels with average between-row readings to demonstrate that model estimates are within the realm of possibility. The average combined between- and within-row values show only a modest elevation in nitrate levels, against the simulated estimates which appear exaggerated. It might even be reasonable to question the overall accuracy of the suction tube readings. One undeniable feature of graph 1 is that sandy soils (at field capacity) quickly flush their excess nitrates.

Graph 1 -- Field measures of nitrate leaching at 120 cm. compared with model generated estimate.

2. Anecdotal evidence from field experience.

The second validation of model accuracy is the experience of early July. Just as the model was indicating a nitrogen deficiency stress in the crop, a similar warning was being given by the petiole sap test, administered by the Anoka Sand Plains staff. The grower was questioned about these assessments at the Becker field day on July 7th; he agreed that the crop was beginning to show signs of nitrogen stress, but was held off by weather (until July 13th) from applying the fourth and final nitrogen application.

Graph 2 show the (simulated) crop stress response to a nitrogen deficiency, including the ability to bounce-back when sufficient nitrogen is subsequently applied. Between May 15th (emergence) and July 5th, the crop experienced no appreciable nitrogen stress. For the following 8 days, however, the simulated crop fell short of the reference crop potential nitrogen uptake by as much as 22 kg/ha. After nitrogen was applied by the grower on July 13th the crop made up much of its loss, but a permanent 6 kg/ha loss in total crop potential carried through the rest of the season.

Graph 2 -- Simulated crop nitrogen deficit totaled 6 kg/ha at season end.

Graph 3 shows the same effect, but in terms of total crop N uptake. Compared to the final crop N uptake of 220 kg/ha, the loss of 6 kg/ha in added potential uptake seems small (shaded area at top). But with a high value crop like potatoes, costs multiple rapidly; and the economics of high nitrogen inputs quickly becomes apparent. If the crop potential is 500 (100 lb.) bags, and in a good market they can bring (across the whole yield) 5 cents a lb., the total field value is $2,500 per acre. A 2-percent yield reduction equals 10 bags or 1000 lbs, at a potentially cost the grower $50/acre. The growers marginal cost for nitrogen (or irrigation water for that matter) is negligible by comparison. As profit-maximizing agents, who wish to minimize the risk of yield loss from crop nitrogen stress, rational growers will continue to apply above optimal levels of fertilizer nitrogen and irrigation water.

Graph 3 -- Total crop nitrogen plus stress loss of potential N uptake.

SECTION 3> Alternative Simulation Results -- testing for better nitrogen and irrigation management options.

During the 1994 season, the grower reportedly applied 45 cm. of irrigation water to the field crop. Yet potatoes grown under similar conditions at the Becker experiment station, using Best Management Practices, needed only 25 cm. of irrigation. The strength of simulation modelling is the power to quickly and easily test alternative field scenarios. For instance, how would the nitrogen mass balance be changed if we assumed that the grower applied only half as much irrigation ?

Holding all other factors constant, table 5. shows the results of a simulation for which the amount of grower-supplied irrigation is cut in half -- 22.5 cm. instead of 45 cm. By definition, the nitrate contribution from the irrigator (measured at 22 ppm.) is also reduced by half -- to 55 kg/ha from 110 kg/ha. While total crop nitrogen uptake is unchanged at 220 kg/ha, the grower-supplied nitrogen now accounts for a greater portion (68%) of the total N uptake. Total nitrate leaching is reduced nearly 20-percent, both from the grower-supplied nitrogen and background sources.

Table 5. -- Alternative 1. Reduce irrigation schedule by one-half.

Total System Nitrogen Resources		
Grower-supplied N 290	Background nitrogen sources	300
	- initial active organic	215
	- initial inorganic profile	30
	- seasonal irrigation	55
Total Crop Nitrogen Uptake <220>		
Grower-supplied Crop N <150>	Background Crop N <70>	
Post-harvest Nitrogen Conditions		
Grower-supplied nitrogen	Background N sources	
- residual top mass <0>	- final active organic <115>	
- residual root <15>	- final Inorganic profile <35>	
- denitrification <10>	- denitrification <15>	
Total Nitrogen Leached @ 120 cm.		
Leachate <115>	Leachate <65>	

----- Units in Kg/Ha --

A second alternative management strategy can also be easily tested using the simulation model. Could the grower have taken a nitrogen credit for the irrigation water and thereby reduced his level of fertilizer nitrogen applications ? Table 6. displays the results of simulating a 30 kg/ha credit for the irrigator N contribution, which translate into about a 10-percent reduction in the overall level of grower-supplied nitrogen. The combined affect of a 50-percent irrigation cutback and a 10-percent reduction in grower-supplied N, still fails to lower total crop N uptake below 220 kg/ha. Total nitrate leaching from the grower-supplied source, however, is reduced another 20-percent. Compared to the baseline scenario outlined in table 4., nitrate leaching could have been reduced by one-third, without negatively impacting crop development, had the grower cut irrigation by one-half and decreased his nitrogen applications by 10-percent. Both crop management changes would have been in line with (University of Minnesota) extension recommendations for best management practices.

Table 6. -- Alternative 2. Reduce irrigation by half and grower-supplied N by 10-percent.

Total System Nitrogen Resources

Grower-supplied N 260	Background nitrogen sources	300
	- initial active organic	215
	- initial inorganic profile	30
	- seasonal irrigation	55

Total Crop Nitrogen Uptake <220>

Grower-supplied Crop N <140>	Background Crop N <80>

Post-harvest Nitrogen Conditions

Grower-supplied nitrogen	Background N sources
- residual top mass <0>	- final active organic <115>
- residual root <15>	- final Inorganic profile <32>
- denitrification <10>	- denitrification <13>

Total Nitrogen Leached @ 120 cm.

Leachate <95>	Leachate <60>

----- Units in Kg/Ha --