Potential use of precision conservation techniques to reduce nitrate leaching in irrigated crops

J.A. Delgado and W.C. Bausch

ABSTRACT: There is a continuing need to develop advanced nitrogen (N) management practices that increase N use efficiencies and reduce nitrate-nitrogen (NO_3-N) leaching. Our goal was to evaluate the use of geographic information systems (GIS), global positioning systems (GPS), modeling and remote sensing for reducing residual soil NO_3-N and NO_3-N leaching in a center-pivot irrigated corn (*Zea mays* L.) field. Specific objectives were: 1) to determine if productivity zones delineated using precision agriculture technologies could also correctly identify unique areas within corn fields that differed in residual soil NO_3-N and NO_3-N leaching potential; and 2) evaluate the potential to use remote sensing of crop productivity to reduce NO_3-N leaching losses. This study was conducted in northeastern Colorado during the 2000 and 2001 growing seasons in a 70 ha (173 ac) center-pivot irrigated commercial cornfield. For the first objective, initial and final soil samples after harvesting were collected at known locations in high, medium and low productivity areas across this field. For the second objective initial and final soil samples after harvesting were collected in a low productivity area where *"in season"* N management was conducted based on remote sensing data. Crop yields and total N were determined on plant samples located at the soil sampling coordinates. The N reflectance index was used to determine the *"in season"* N application. Remote-sensing-based N fertilization treatment occurred whenever the mean N reflectance index was lower than 0.95 and/or more than 50 percent of the area had an N reflectance index less than 0.95. For both studies, the nitrate leaching economic analysis package and GIS were used to evaluate NO_3-N leaching losses. We found that GIS, GPS, and modeling technologies can be used to identify and simulate the spatial residual soil NO_3-N patterns. Productivity zones delineated using precision agriculture technologies identified areas within corn production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. This spatial variability was negatively correlated with the soil texture ($P<0.001$), having lower residual soil NO_3-N on the lower productivity sandier areas, which also had a higher NO_3-N leaching potential. The N Reflectance Index method can maximize the synchronization of *"in season"* N applications with corn N uptake needs to increase N use efficiencies and reduce NO_3-N leaching losses by 47 percent when compared to traditional practices ($P<0.0001$).

Keywords: Corn, GIS, GPS, nitrate leaching, nitrogen, nitrogen management, NLEAP, precision conservation, remote sensing

Nitrogen (N) is a key nutrient that contributes to higher yields and sustainability across agricultural systems worldwide. This important nutrient is susceptible to losses via surface runoff transport, leaching and gaseous pathways (Follett and Delgado, 2002). These losses impact surface and groundwater quality (Newbould, 1989; Follett et al., 1991).

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Researchers have correlated land use practices with groundwater nitrate (NO_3-N) levels (Hallberg, 1989; Juergens-Gschwind, 1989). Although average N use efficiency has been reported to be about 50 percent (Baligar et al., 2001), it is possible to use best management practices to reduce NO_3-N leaching losses to a minimum (Delgado, 1998; Delgado, 2001; Hergert, 1986; Meisinger and Delgado, 2002; Randall and Mulla, 2001; Schepers et al., 1995; Smika et al., 1977; Thompson and Doerge, 1996a; 1996b; Westermann et al., 1988).

Delgado (2001) reported that the finer textured sandy loam areas cropped in irrigated barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), and potato (*Solanum tuberosum* L.) had higher residual soil NO_3-N content of 42, 51, and 136 kg N ha^{-1}, (38, 46, and 122 lb ac^{-1}) respectively, than the 20, 44, and 109 kg N ha^{-1} (18, 39, and 97 lb N ac^{-1}) respectively, observed for the coarser loamy sand areas. The correlation between soil texture and residual soil NO_3-N, with lower content of residual soil NO_3-N on the sandier areas of irrigated fields, was also reported by Delgado et al. (2001a), Delgado (1999), Delgado and Duke (2000), and Meisinger and Delgado (2002).

New technologies such as global positioning systems (GPS) and geographic information systems (GIS), can be used to manage N taking into consideration spatial variability to increase N use efficiencies (Bausch and Delgado, 2003; Gotway et al., 1996; Ferguson et al., 1996; Hergert et al., 1996; Khosla et al., 2002; Redulla et al., 1996). Remote sensing techniques combined with GPS and GIS techniques can be applied to production fields to manage N inputs (Bausch and Delgado, 2003; Bausch and Diker, 2001; Scharf et al., 2002). Remote sensing can reduce N inputs without reducing yields (Bausch and Delgado, 2003).

Precision conservation was defined as the integration of spatial technologies such as GPS, GIS, and remote sensing and the ability to analyze spatial relationships within and among mapped data (Berry et al., 2003). Precision conservation can link weather, hydrologic factors and spatial and temporal variability across the field to describe off-site transport of nutrients. Nutrient managers can use these technologies to develop conservation practices that reduce off-site transport of soil and nutrients (Berry et al., 2003). Bausch and Delgado (2003) reported that remote sensing reduced N applications from 214 to 102 kg N $ha^{-1}yr^{-1}$ (191 to 91 lb N ac^{-1} yr^{-1}) without reducing yields.

Crop spectral reflectance can be used to determine the N status and as a tool to improve *"in-season"* N management practices so that N applications are synchronized with crop N uptake (Al-Abbas et al., 1974; Bausch and Diker, 2001; Scharf et al., 2002; Stanhill et al., 1972). Bausch and Duke (1996) developed the N reflectance index capable of assessing N status in corn. The N reflectance index is the near-infrared canopy reflectance divided by the green canopy. The ratio of this reflectance from a monitored area is divided by ratio of a well fertilized reference area N reflectance index = $(NIR/G)_{sample}$ / $(NIR/G)_{reference}$. Other indices that can be used to determine crop N status include the normalized difference vegetation indices (Tucker, 1979) and the plant N spectral index (Stone et al., 1996).

In agricultural production, evaluation of the effectiveness of nutrient conservation practice is difficult. Computer simulation models can be used to solve this problem (Delgado et al., 2000). The Nitrate Leaching and Economic Analysis Package is a tool that can be used to conduct a rapid site-specific evaluation of practices for N management (Shaffer et al., 1991). The Nitrate Leaching and Economic Analysis Package can be used to evaluate individual fields as well as spatial variability within fields or larger regions (Delgado, 2004; Delgado et al., 2001b; Delgado and Follett, 2004; Hall et al., 2001; Wylie et al., 1994). Beckie et al. (1994) and Khakural and Robert (1993) reported that this model has been found to perform similarly to the Crop Estimation Through Resource and Environment Synthesis (Ritchie et al., 1985), the Erosion/Productivity Impact Calculator (Williams, 1982), the Nitrogen Tillage Residue Management (Shaffer and Larson, 1987), and LEACHM-N, (Wagenet and Hutson, 1989). Models can help us to assess the effects of nutrient management practices on N use efficiencies. Our goal was to evaluate the use of GIS, GPS, modeling and remote sensing technologies for reducing residual soil NO_3-N and NO_3-N leaching in a center-pivot irrigated cornfield. We conducted two studies to assess how these technologies can be used as precision conservation tools.

Study one was conducted to determine if productivity zones delineated using precision agriculture technologies could correctly identify unique areas within corn production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. Our hypothesis is that productivity zones are correlated to the residual soil NO_3-N and NO_3-N leaching losses in center-pivot irrigated corn. We suggest that by identifying these productivity zones we could assist in identifying unique NO_3-N leaching areas within a field.

Study two was a modeling evaluation of the potential to use remote sensing of crop productivity to reduce NO_3-N leaching losses. Our hypothesis is that by managing *'in situ'* N applications the synchronization of N applications with N uptake by the crop is maximized and residual soil NO_3-N and NO_3-N leaching losses can be minimized. For both studies, the Nitrate Leaching and Economic Analysis Package was used to evaluate residual soil NO_3-N and NO_3-N leaching losses.

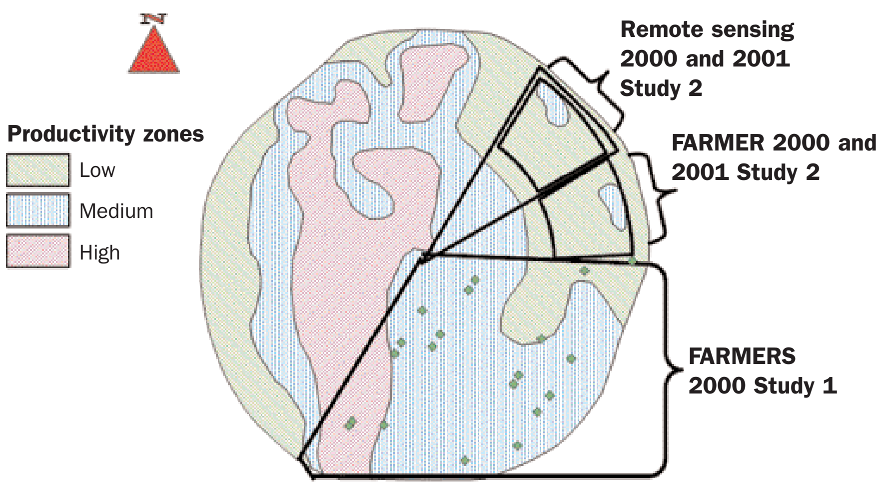
Methods and Materials

Study One

Field site. This research was conducted during the 2000-growing season in a 70 ha (173 ac) center pivot irrigated field located northeast of Wiggins, Colorado. We used GIS, GPS, and modeling to determine if productivity zones delineated using precision agriculture technologies could correctly identify unique areas within corn production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. Fleming et al. (1999) identified the productivity zones based on soil color from aerial photographs, topography, and the farmer's past management experience for this site (Figure 1).

Collection and analysis of soil and plant samples. Geo-referenced soil samples were collected in spring prior to fertilizer applications, and after harvest (Figure 1). Plant samples were collected, and yield was determined from the same locations as the soil samples. At each location two soil samples were collected 0.3 m (1 ft) apart and composited by depth. Fall samples were collected 0.3 m (1 ft) apart, where one core was centered between corn rows and the other near the corn row. A hydraulic soil sampler was used to collect soil samples to 1.5 m (5 ft) depths by 0.3 m (1 ft) increments. Initial soil samples were used to measure soil texture and bulk densities. At each sampling location bulk densities were measured with the core method. Other initial soil samples measurements included: percent coarse fragments by

Figure 1
Layout of the random plots monitored in study one across three productivity zones during the 2000 growing season (green diamonds). The remote sensing wedge in study two was the location were the nitrogen (N) fertigation management "in season" was conducted with the N reflectance index method. The farmer wedge was the similar size truncated area for low productivity zone for farmer's traditional practices.



weight and by volume, percent organic matter, pH, cation exchange capacity, and initial soil water content. Soil samples were air-dried, ground, and stored in sealed plastic bags. Major soil types at the site were Bijou loamy sand with one to three percent slope (*Coarse-loamy, mixed, superactive, mesic Ustic Haplargids*), Bijou loamy sand with zero to one percent slope, Valentine Dwyer fine sand (*Mixed, mesic Ustic Torripsamments*), and Valentine fine sand, hilly (*Mixed, mesic Typic Ustipsamments*).

Two sub-samples (20 g or 0.71 oz) from each composite sample were prepared for chemical analysis by extracting with 100 ml (3.4 oz) of 2N KCl, shaking for one hour, and filtering the liquid fraction. The extracts were analyzed for NO_3-N and NH_4-N by automated flow injection analysis using a Technicon[1] auto analyzer (Technicon Industrial Systems, Elmsford, New York).

Before the farmer harvested the field, five plant samples were collected at each sampling point to measure total aboveground biomass, and to determine the N content by compartments. Plant samples were separated by leaves, stems, ears, cobs, husks, and grain. All plant samples were oven dried at 55° C (131° F), and dry grain yields were determined. Plant compartments were ground, and analyzed for total C and N content by combustion using a Carlo Erba automated C/N analyzer.

Farmer practices. The whole field received the same tillage operations during 2000, which consisted of disking and ripping. Preplant fertilizer application was followed by mulch treading for fertilizer incorporation and seedbed preparation. Time and rate of fertilizer applications are shown in Table 1. Corn (Pioneer hybrid 34G81, planophyle canopy) was planted on May 12, 2000 at 83,000 seeds ha^{-1} (33,601 seeds ac^{-1}). Row direction was 32° from north with a row spacing of 0.76 m (2.49 ft).

Nitrate leaching economic analysis package inputs. The nitrate leaching economic analysis package version 1.20 was used to determine if productivity zones delineated using precision agriculture technologies could also correctly identify unique areas within corn production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. Irrigation, N fertilizer application, initial soil NO_3-N, N fertilizer, NO_3-N background in irrigation water, planting, harvesting, cultivation, and other agricultural management practices were collected and entered into the nitrate leaching economic analysis package. Crop planting and harvesting dates, N-, water-, and cultural-management inputs and timing, soil and climate information, and yield were collected and entered into nitrate leaching economic analysis package. Irrigation amounts and time were entered in the model. Several well water samples were collected from June to August to determine NO_3-N in the groundwater.

The U.S. Department of Agriculture Agricultural Research Service irrigation scheduling computer program, called SCHED, developed by Buchleiter et al. (1995) was used to provide the farmer with weekly irrigation schedules based on estimated crop evapotranspiration. An automated weather station located near the northwest edge of the field was used to measure climatic data.

Nitrate Leaching Economic Analysis Package outputs. The Nitrate Leaching and Economic Analysis Package was used to simulate residual soil NO_3-N and NO_3-N leaching. Simulated and measured residual soil NO_3-N (0 to 1.5 m, or 0 to 5 ft) were compared using SAS REG (SAS Institute, 1988). For these analyses, the linear intercept (b0) and slope (b1) were tested with SAS REG for differences from zero and one, respectively. The outputs for residual soil NO_3-N and NO_3-N leaching, and the observed sand content and residual soil NO_3-N were analyzed using geostatistical methods (kriging) and

Table 1. Date, operation, and amount of fertilizer applied in Study One during the 2000 growing season.

Date	Operation	Fertilizer kg ha^{-1} N	P	K
April 14	Preplant*	6	17	56
May 12	Starter[1]	28	34	
June 24	Fertigation	56		
July 2	Fertigation	56		
July 9	Fertigation	34		
July 14	Fertigation	34		
July 22	Fertigation	34		
Total *"fertigation"*		*214*		
Total growing season		248	51	56

* There was an application of 6 kg S ha^{-1} and 1 kg Zn ha^{-1}

Table 2. Date, operation, and amount of fertilizer applied in Study Two during the 2000 and 2001 growing seasons for the *"in season"* farmer and remote sensing nitrogen (N) management fertigations.

	Date	Operation	Farmer fertilizer* (kg ha^{-1}) N	Remote sensing* (kg ha^{-1}) N
Year = 2000				
	April 14	Preplant	6	6
	May 12	Starter	28	28
	June 24	Fertigation	56	
	July 2	Fertigation	56	
	July 9	Fertigation	34	34
	July 14	Fertigation	34	34
	July 22	Fertigation	34	34
Total *"fertigation"*			*214*	*102*
Total growing season			248	136
Year = 2001				
	April 25	Preplant	6	6
	May 15	Starter	28	28
	July 2	Fertigation	67	
	July 9	Fertigation	34	
	July 13	Fertigation		34
	July 14	Fertigation	34	
	July 16	Fertigation		34
	July 17	Fertigation	34	
	July 23	Fertigation	45	
	July 25	Fertigation		34
Total *"fertigation"*			*214*	*102*
Total Growing season			248	136

* Each year there was an application of 51 kg P ha^{-1}; 56 kg K ha^{-1}; 6 kg S ha^{-1} and 1 kg Zn ha.$^{-1}$

mapped. For additional details on how to use the Nitrate Leaching and Economic Analysis Package to evaluate best management practices, see Shaffer et al. (1991) and Delgado (2001).

Study Two

Study two was a modeling evaluation on the potential to use remote sensing to reduce NO_3-N leaching losses. The low productivity area within the field was evaluated. The soil type in this area of the field was classified as Valentine fine sand. Surface soil in this area contained 92 percent sand, two percent silt, and six percent clay (1.5 m or 5 ft).

This study was conducted during 2000 and 2001 at the same site described above. Soil and plant samples were collected, processed and analyzed with the same procedures as described above. Farmer practices for 2000 were similar to those described above. Time and rate of fertilizer applications are shown in Table 2.

Remote sensing "in season" N application. To control application rates for the remote sensing nitrogen managed area, a wedge shaped area was established for application of "as needed" nitrogen by the crop (Figure 1). The wedge area was truncated to represent only 3.2 ha (7.9 ac) within the low productivity zone, which was the area used for making N application decisions (Figure 1). Four samples were collected inside the remote sensing truncated wedge low productivity area. A similar 3.2 ha (7.9 ac) farmer N management was located with GPS in the field, where two samples were collected.

The *"in season"* N application in this wedge area was based on the N reflectance index (Table 2). If the mean N reflectance index within the truncated wedge was lower than 0.95 and/or more than 50 percent of the truncated area had an N reflectance index less than 0.95, the remote sensing wedge area was fertigated with 34 kg N ha^{-1} (30 lb N ac^{-1}). Since the N reflectance index need reference areas non-deficient in N, reference areas were established in 2000 and 2001 (Bausch and Delgado, 2003). The Bausch et al. (1990) boom-type data acquisition system mounted on a high-clearance tractor for field access was used to measure corn canopy radiance and incoming irradiance simultaneously. The sensor package consisted of two Exotech 100BX four-band radiometers (Exotech, Inc.) and a Campbell Scientific Inc. 23X datalogger to sample and store radiometer sensor voltages as well as time of measurement. Radiant energy in discrete wavebands in the blue, green, red, and near-infrared similar to the Landsat Thematic Mapper wavebands, i.e., 450 to 520 nm, 520 to 600 nm, 630 to 690 nm, and 760 to 900 nm, respectively, were measured with the radiometers. Data acquisition started around 10:30 a.m. and continued for about 2.5 hour. Longitude and latitude of each data point was determined with a real-time differential GPS unit (Racal Landmark IV) (Bausch and Delgado, 2003). This method allowed quick processing of the canopy reflectance to develop accurate maps about the N status across the field in GIS to N applications maps. In comparison, the farmer in situ N management practices for N fertigations outside of the remote sensing wedge were applied at the farmers' discretion.

Grain yields were obtained across the field with a combine equipped with a yield monitor and GPS for the years 2000 and 2001. This yield monitor data was used to determine yields in the truncated wedge where *"in season"* N was applied with remote sensing and the similar size truncated wedge area with farmer N *"in situ"* management practices. The same machine and yield monitor were used for both years.

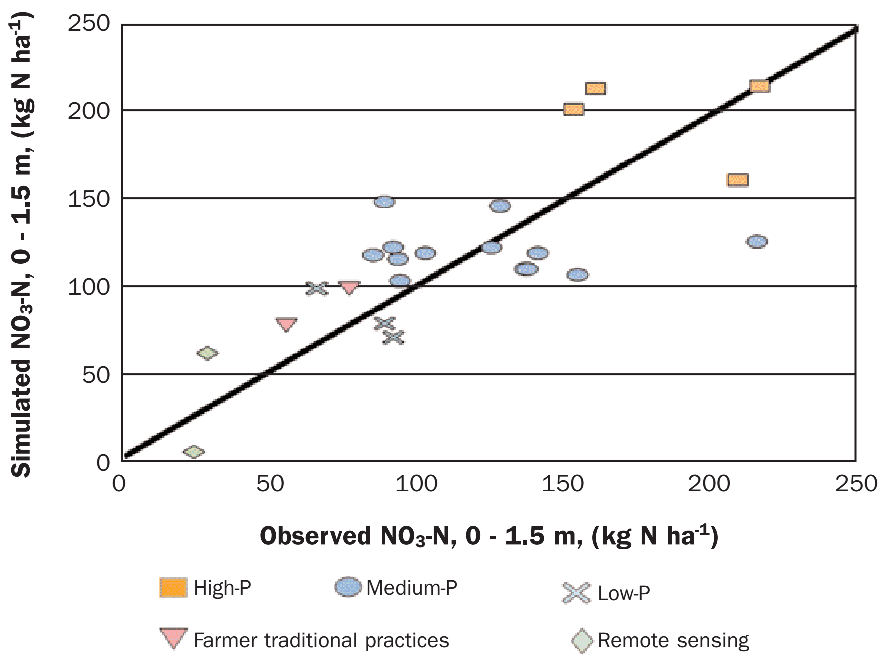
Results and Discussion

Study One

Our results showed that GIS and GPS technologies can be used with productivity zones delineated as described by Fleming et al. (1999) to identify unique areas within corn production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. Modeled estimates using the Nitrate Leaching and Economic Analysis Package (NLEAP) explained 58 percent of the measured residual soil NO_3-N in the root zone ($P<0.0001$; Figure 2). The y intercept and slope values of the linear model relating measured and predicted values were not significantly different from zero and one, respectively (Figure 2). Follett et al. (1994) found similar strong relationships between the Nitrate Leaching and Economic Analysis Package, predicted and measured, values in irrigated corn.

Figure 2

Simulated and observed residual soil nitrate-nitrogen (NO_3-N) in the top 1.5 m of soil for the high, medium and low productivity areas (High-P, Medium-P, and Low-P, respectively) and for remote sensing and farmer's traditional practices truncated wedges.



Under the same management, the productivity zones were correlated to the residual soil NO_3-N and NO_3-N leaching potential losses. The residual soil NO_3-N was greater in high productivity zones (174 kg NO_3-N ha^{-1} or 155 lb NO_3-N ac^{-1}) than medium (112 kg NO_3-N ha^{-1}; $P<0.01$; 100 lb NO_3-N ac^{-1}) for the medium and low (73 kg NO_3-N ha^{-1}; $P<0.01$; 65 lb NO_3-N ac^{-1}) productivity zones (Figure 2). The dry weight yields of 12.7, 11.4, and 10.9 Mg ha^{-1} (5.7, 5.1, and 4.9 t ac^{-1}) in high, medium and low productivity zones followed the same trend and response as predicted (Table 3). The dry grain yield was greater in high productivity zones (12.7 Mg ha^{-1} or 5.7 t ac^{-1}) than for the low (10.9 Mg ha^{-1}; $P<0.05$; 4.9 t ac^{-1}) and than the medium (11.4 Mg ha^{-1}; $P<0.10$; 5.1 t ac^{-1}) productivity zones. Grain N content and total N uptake followed a similar trend, higher in the high productivity zone (Table 3).

We suggest that by identifying these productivity zones, we can assist in identifying specific NO_3-N leaching areas within a field. Simulated residual soil NO_3-N was correlated with the observed (Figure 2). The simulated residual soil NO_3-N was higher for the high productivity zones (Table 4). The simulated 194.5 kg NO_3-N ha^{-1} (174 lb NO_3-N ac^{-1}) leaching losses were significantly higher for the sandier lower productivity zones ($P<0.05$; Table 4).

Table 3. Studies One and Two total nitrogen (N) fertilizer inputs, grain yield, grain N content, and total aboveground N content.

Study	Year	*Productivity zone	†Management system	Fertilizer applied growing season kg N ha^{-1}	Dry grain yield Mg ha^{-1}	Grain N uptake (kg N ha^{-1})	Total N uptake (kg N ha^{-1})
One	2000	High	Farmer	248	12.7 a	171.5 a	233.9 a
		Medium	Farmer	248	11.4 ab	150.0 b	203.3 b
		Low	Farmer	248	10.9 b	140.5 b	188.4 b
Two	2000	Low	Farmer	248	10.9 a	140.5 a	184.5 a
		Low	Remote sensing	136	11.3 a	137.9 a	170.3 a
Two	2001	Low	Farmer	248	9.9 a	132.4 a	166.3 a
		Low	Remote sensing	136	10.1 a	124.4 a	153.7 a

* Within a column, for study one productivity zones with different letters are significantly different at least significant difference $P < 0.05$.

† Within a column, for study two by year, management system with different letters are significantly different at least significant difference $P < 0.05$.

Table 4. Study One and Two simulated residual soil and leached nitrate (NO_3-N).

Study	Year	*Productivity zone	†Management system	Simulated soil NO_3-N (kg N ha^{-1})	Simulated leached NO_3-N (kg N ha^{-1})
One	2000	High	Farmer	195.6 a	108.6 c
		Medium	Farmer	125.9 b	138.0 b
		Low	Farmer	82.5 c	194.5 a
Two	2000	Low	Farmer	82.5 b	194.5 a
		Low	Remote sensing	50.4 a	94.6 b
Two	2001	Low	Farmer	66.1 a	179.2 a
		Low	Remote sensing	17.9 a	101.5 b

* Within a column, for study one productivity zones with different letters are significantly different at least significant difference P < 0.05.

† Within a column, for study two by year, management system with different letters are significantly different at LSD P < 0.05.

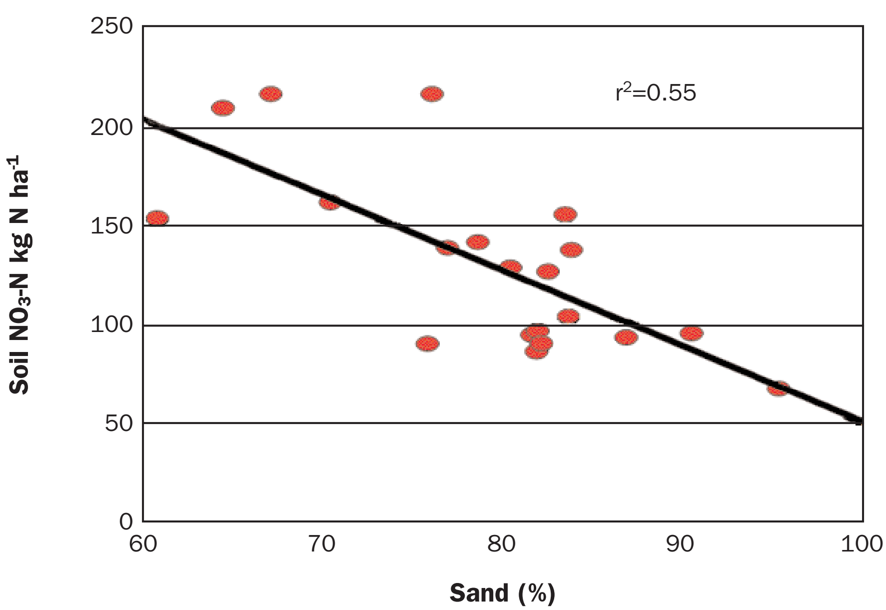
The residual soil NO_3-N values were negatively correlated with sand content ($r^2 = 0.55$, $P<0.001$) (Figure 3). The 68 percent sand content in the top 1.5 m (5 ft) was significantly lower for the high productivity zones than the sand content for the medium and low productivity zones ($P< 0.01$). The sand content of 80 percent in the top 1.5 m (5 ft) for the medium productivity zone was lower than the 88 percent for the low productivity zone ($P< 0.10$), although not significantly. The soil texture in the top 1.5 m (5 ft) of soil across the most productive area was dominated by the Bijou soil series that had a lower sand content (68 percent) while the Valentine soil series dominated the area with the lower productivity and had a higher sand content (88 percent). Our results also agreed with those from Delgado (1999), Delgado (2001), and Delgado et al. (2001a) which simulated the effects of soil texture on residual soil NO_3-N.

The simulated net NO_3-N leaching losses were 49, 78, and 135 kg of NO_3-N ha^{-1} (44, 70, and 121 lb NO_3-N ac^{-1}) for the high, medium and low productivity zone areas, respectively (based on total NO_3-N leaching values in Table 4). The net NO_3-N leaching losses were calculated as: net NO_3-N leaching loss = NO_3-N leached from the root zone - NO_3-N in the groundwater added as irrigation water to the field. The irrigation water had an average of about 60 kg NO_3-N ha^{-1} (54 lb NO_3-N ac^{-1}).

The spatial variability for sand content percentage is shown in Figure 4. The spatial variability of the observed residual soil NO_3-N is shown in Figure 5. The areas with the highest residual soil NO_3-N across the field are also the areas with the lower sand content (Figures 4 and 5). The simulated residual soil NO_3-N is shown in Figure 6 and is similar to the observed residual soil NO_3-N (Figures 5 and 6). The spatial variability of the leached NO_3-N is shown in Figure 7. The larger areas with higher NO_3-N leaching potential are those sandier areas of the field (Figures 4 and 7).

This paper presents the first GIS and the Nitrate Leaching Economic Analysis Package evaluation of a commercial irrigated cornfield, taking into consideration the spatial differences in productivity zones delineated with precision farming technologies. There is potential to use GPS, GIS and modeling to evaluate residual soil NO_3-N and NO_3-N leaching potential across productivity zones. Our results show the capability of using the Nitrate Leaching Economic Analysis Package with GIS to evaluate the effects of hydrological properties, productivity zones, soil texture, and N management of irrigated agricultural systems to identify the areas with higher NO_3-N leaching potential. We suggest that by identifying these landscape sensitive areas, we can manage them differently to increase N use efficiencies and reduce N losses.

Figure 3
Correlation between the residual soil nitrate-nitrogen (NO_3-N) in the top 1.5 m of soil with the respective sand content at each site during the 2000 growing season.



Study Two

Study Two was a modeling evaluation of the potential to use remote sensing of crop productivity to increase the synchronization of N applications with N uptake by corn.

The remote sensing wedge area received 136 kg N ha^{-1} yr^{-1} (122 lb N ac^{-1} yr^{-1}) (Table 2), resulting in a dry yield of 11.3 and 10.1 Mg ha^{-1} (5.0 and 4.5 t ac^{-1}) for the 2000 and 2001 growing seasons, respectively (Table 3). Farmer N management had similar yield of 10.9 and 9.9 Mg ha^{-1} (4.9 and 4.4 t ac^{-1}) for 2000 and 2001, respectively (Table 3), even though it received 248 kg N ha^{-1} yr^{-1} (222 lb N ac^{-1} yr^{-1}) of *"in season"* N applications. By reducing the *"in season"* N application by 112 kg N ha^{-1} (100 lb N ac^{-1}) the residual soil NO_3-N after harvest was significantly reduced to 24 kg NO_3-N ha^{-1} yr^{-1} (21 lb NO_3-N ac^{-1} yr^{-1}) when compared to farmer practices of 67 kg NO_3-N ha^{-1} yr^{-1} (60 lb NO_3-N ac^{-1} yr^{-1}) ($P<0.05$; Figure 2). Model evaluations predicted average leaching loss of 98.1 kg NO_3-N ha^{-1} yr^{-1} (88 lb NO_3-N ac^{-1} yr^{-1}) for the remote sensing managed wedge, lower than the 186.9 kg NO_3-N ha^{-1} yr^{-1} (167 lb NO_3-N ac^{-1} yr^{-1}) (Table 4). The remote sensing *"in season"* N management reduced total NO_3-N leaching losses by 51 and 43 percent for the 2000 and 2001 growing seasons, respectively (Table 4). The remote sensing *"in season"* N management reduced the net NO_3-N leaching losses by 74 and 65 percent. These lower predicted NO_3-N leaching losses for the remote sensing wedge area correspond closely to lower N inputs of 112 kg N ha^{-1} yr^{-1} (100 lb N ac^{-1} yr^{-1}). This study is the first test of the goodness of fit for the Nitrate Leaching Economic Analysis Package to predict residual soil NO_3-N when using remote sensing to manage *'in situ'* N applications and the first evaluation of the potential to use remote sensing to minimize NO_3-N leaching. Remote sensing is a potential management tool to reduce NO_3-N leaching losses and increase N use efficiencies.

Summary and Conclusion

The combination of the Nitrate Leaching Economic Analysis Package and GIS is a powerful tool to evaluate the spatial residual soil NO_3-N variability in irrigated corn. This spatial variability was correlated with soil texture and productivity zones and agreed with results previously presented by Delgado (1999), Delgado (2001) and Delgado et al. (2001a) for barley, canola, lettuce (*Lactuca sativa* L) and potato. The areas with coarser texture had lower yield, lower residual soil NO_3-N content and a higher NO_3-N leaching potential. The N Reflectance Index method as applied by Bausch and Delgado (2003) for irrigated corn systems can maximize the synchronization of *"in season"* N applications with corn N uptake needs, significantly increasing N use efficiencies while reducing NO_3-N leaching losses by 47 percent when compared to farmer traditional practices. This study shows that there is potential to use remote sensing, GPS, GIS and models to reduce residual soil NO_3-N and NO_3-N leaching losses in center-pivot irrigated corn fields. Precision conservation

Figure 4
Spatial distribution of sand content in the top 1.5 m of soil for Study One across the different productivity zones during the 2000 growing season.

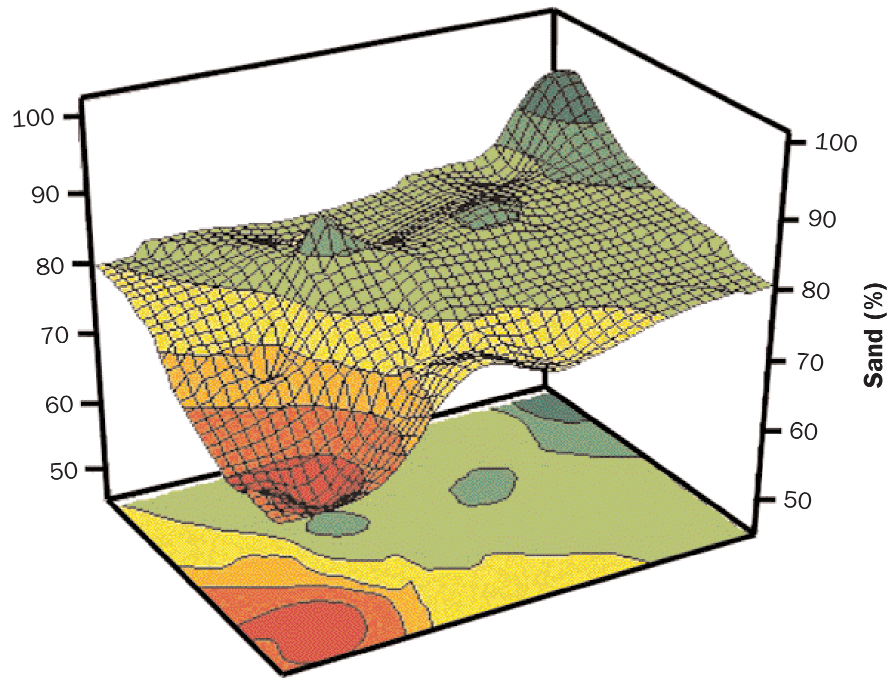


Figure 5
Spatial distribution of observed residual soil NO_3-N in the top 1.5 m of soil for Study One across the different productivity zones during the 2000 growing season.

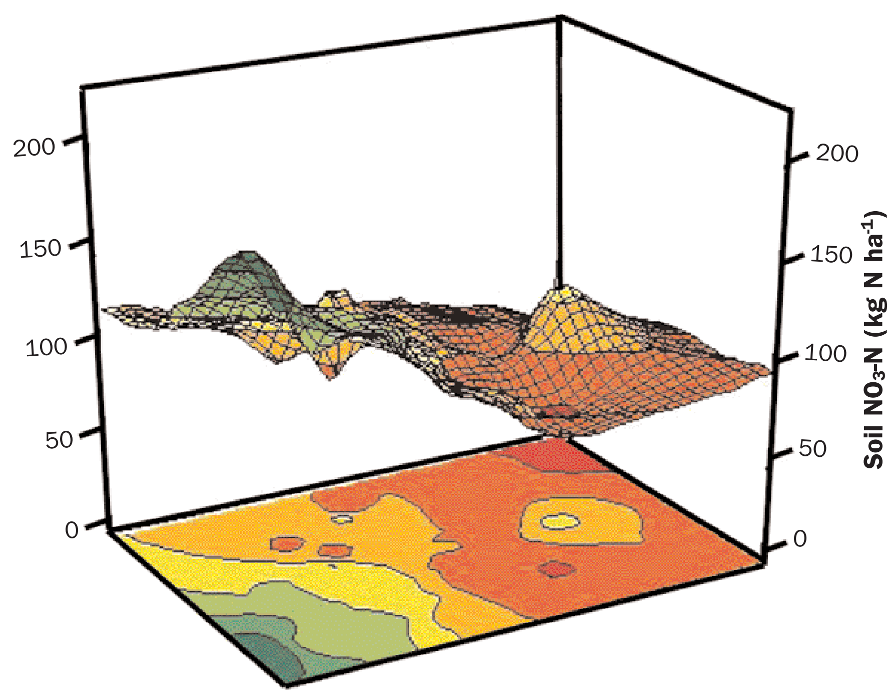


Figure 6

Spatial distribution of simulated residual soil nitrate-nitrogen (NO_3-N) in the top 1.5 m of soil for Study One across the different productivity zones during the 2000 growing season.

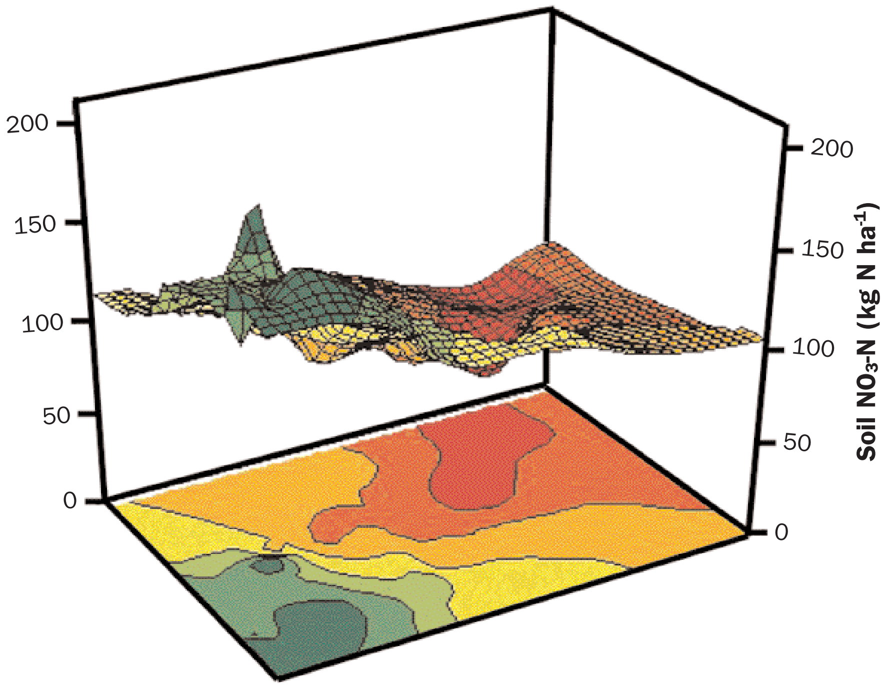
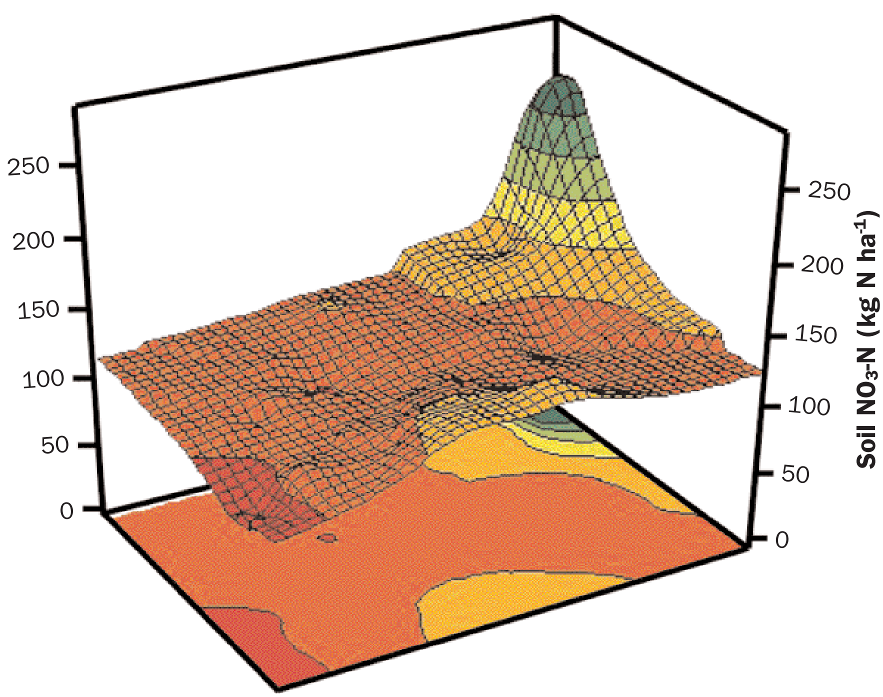


Figure 7

Spatial distribution of predicted nitrate-nitrogen (NO_3-N) leaching from the root zone of corn (1.5 m depth) in Study One across the different productivity zones during the 2000 growing season.



technologies can be used to evaluate the effects of best management practices and minimize NO_3-N leaching.

Endnote

[1]Names are necessary to report factually on available data; however, the U.S. Department of Agriculture (USDA) neither guarantees not warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may be suitable.

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