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An index approach to assess nitrogen losses to the environment☆

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ABSTRACT

Nitrogen (N) losses from agriculture are negatively impacting groundwater, air, and surface water quality. New tools are needed to quickly assess these losses and provide nutrient managers and conservationists with effective tools to assess the effects of current and alternative management practices on N loss pathways. A new N-Index tool was developed in spreadsheet format, allowing prompt assessments of management practices on agricultural N losses. The N-Index tool was compared with experimental field data and shown to estimate the effects of management practices on N loss pathways (probability, $P < 0.001$). The N-Index correctly assessed the nitrate nitrogen (NO_3-N) leaching losses when tested against measured NO_3-N leaching data and atmospheric N losses collected over multiple years (annual basis) and locations. The N-Index tool was developed with international cooperation from several countries and there is potential to use this tool at the international level.

☆ The NIT-1 Tool is intended for nutrient management. The USDA developers or other cooperative institutions do not guarantee the use of this electronic file. The user assumes all the risk for using this file and for interpreting the results. Names are necessary to report factually of available data; however the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may be suitable. The mention of commercial names is just to present the facts. USDA and other cooperating institutions do not guarantee the function for the product, nor do we recommend the use of any product over the use of another.
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Abbreviations: NIT-1, N-Index Tier-1 spreadsheet tool; NLEAP, nitrate leaching and economic analysis package.
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1. Introduction

Agricultural-related nitrogen (N) losses are negatively impacting groundwater, air, and surface water quality (Antweiler et al., 1996; Follett and Walker, 1989; Follett et al., 1991; McCracken et al., 1994; Mitsch and Day, 2006; Milburn et al., 1990; Owens and Edwards, 1994). The complexities of the N cycle have made estimating these losses extremely difficult (Delgado, 2002). Today nutrient managers and conservationists need faster and more effective tools to assess the effects of current and alternative management practices on N loss pathways. Biologists, applied ecologists, environmental scientists, and nutrient managers interested in assessing the effects of N management on agricultural N losses to the environment could use a N-Index Tier-1 tool to conduct prompt assessments of management practices (Shaffer and Delgado, 2002; Delgado et al., 2006).

Shaffer and Delgado (2001, 2002) described the tier concept for nitrogen management in relation to the complexity of the data needed to develop viable field management practices. In a tier approach, users judge the tool capabilities versus N management requirements for their project. A Tier-1 level will be a system that rapidly conducts an initial qualitative/quantitative screening to separate the potential impacts of medium, high and very high N losses from low and very low potential impacts (Shaffer and Delgado, 2002; Delgado et al., 2006). A Tier-2 level would involve a more complex level of computation of the N dynamics on a daily schedule using application models. A Tier-3 level will involve a detailed research model with supportive field studies.

A potential application of a Tier-1 N-Index is to assess the N losses to the environment to separate the effects of nitrogen management on medium, high and very high nitrate nitrogen (NO_3-N) leaching loss potential impacts from the low and very low levels based on numeric and non-numeric inputs from users. Similarly, the N-Index would be able to separate and rank the effects of nitrogen management on atmospheric and surface N losses. If needed, the N-Index can be calibrated using local/regional data of N uptake, yields, N cycling, N content in manures, and others local parameters to facilitate the decision making process in identifying the potential, local best management practices and alternatives that reduce N losses.

The N-Index can be used to conduct a quick comparison of a basic scenario in different management alternatives. It has been reported that N losses from agricultural systems can be a source of non-point pollution on the environment (Dzikiewicz, 2000; Hofmann et al., 2004; Vagstad et al., 2000; Mitsch and Day, 2006; Hatano et al., 2005). Similarly, several authors have reported that these N losses can be reduced with the implementation of best nitrogen management practices (Bottcher et al., 1995; Delgado, 2001; Shaffer and Delgado, 2002). Expert systems can contribute in making N management decisions that will reduce N losses (Shaffer and Delgado, 2002; Delgado et al., 2006; Palma et al., 2007; van der Werf et al., 2007).

Field and off-site parameters need to be considered when deciding on nitrogen management practices. Off the field practices, such as buffers, can contribute to reduce N losses to the environment (Dosskey et al., 2005; Hefting et al., 2005; Hey et al., 2005). Shaffer and Delgado (2002) and Delgado et al. (2006) recommended that a practical Tier-1 N-Index tool should be able to integrate best management practices with ecological engineering principles and practices such as use of buffers, account for distance to water bodies, deeper rooting systems, distance to aquifers, and others, to help separate and rank the potential effects of nitrogen management.

Rowe et al. (1999) recommended the principle of using trees as a filtering system to reduce NO_3-N leaching. This principle was tested by Allen et al. (2004) for a pecan–cotton alley cropping system in northwestern Florida, and Palma et al. (2007), van der Werf et al. (2007) and Nair et al. (2007) recommended the same type of system for European systems. Deeper-rooted crops were reported to be alternatives to scavenge NO_3-N that has been leached from previous shallower root rotations (Shipley et al., 1992; Delgado, 1998). These deeper-rooted systems were reported to serve as ecological filter strips that recover and even mine NO_3-N from underground water, reducing the net NO_3-N leaching losses to the environment (Delgado, 1998, 2001; Delgado et al., 2001a,b, 2007). The mining of NO_3-N was reported to happen when the amount of NO_3-N leached from deeper-rooted systems was lower than the amount of NO_3-N added with the underground irrigation water.

The concept of an N-Index has been discussed over the last 20 years (Follett et al., 1991; Shaffer and Delgado, 2002; Delgado et al., 2006). Shaffer and Delgado (2002) discussed the possible advantages and disadvantages of having several N-Indexes. The Williams and Kissel (1991) Leaching Index (LI) has been called the N-Index and is being used by USDA-NRCS personnel to estimate potential NO_3-N leaching based on estimated water available to leach (Van Es et al., 2002; Van Es and Delgado, 2006). One advantage of the LI is that it can be computed by using available soil, precipitation, and irrigation databases. The major disadvantage is that the index does not account for N management practices, N dynamics, N sinks, N uptakes, N sources, residual soil NO_3-N, and/or estimates of NO_3-N leaching (Shaffer and Delgado, 2002). Other N-Indexes discussed by Shaffer and Delgado (2002) were the Movement Risk Index, by Shaffer et al. (1991); the Nitrate Available to Leach Index, by Shaffer et al. (1991); the Residual Soil NO_3-N-Index, by Shaffer et al. (1991); the Nitrate Leached Index, by Shaffer et al. (1991); the Nitrogen Use Efficiency Index, by Bock and Hergert (1991); the Annual Leaching Risk Potential Index, by Pierce et al. (1991); and the Aquifer Risk Index, by Shaffer et al. (1991). None of these indexes have all the necessary features that are included in the Delgado et al. (2006) index.

There has been ongoing interest in developing and testing new N-Indexes. Wu et al. (2005) developed the Nitrate Leaching Hazard Index for irrigated agriculture in California. Wu et al. (2005) reported that their Hazard Index can be used to provide information to growers, so they can voluntarily select management practices that reduce NO_3-N leaching. The Wu et al. (2005) Nitrate Leaching Hazard Index was in concurrence with Delgado (1998, 2001), Shaffer and Delgado (2002) with the concept that crop rotations and rooting depths can be used as management tools under commercial operations to scavenge NO_3-N, minimize NO_3-N leaching, and even mine and recover NO_3-N from underground irrigation waters. Additionally, there is a recently assembled 2006 national working group that is selecting members of universities, extensions, and federal and private sectors to cooperatively work on areas of the N-Index (Delgado et al., 2006). There are several N-Index groups from the US and around the world that are working on this extremely important topic, which has been placed at the forefront of nutrient management priorities.

Shaffer and Delgado (2002) presented a framework to develop a National Nitrate Leaching Index. They reported that their framework should be integrated into an environmental N loss index involving NO_3-N leaching and N losses from surface runoff and erosion. They also suggested a need for an index that accounts for atmospheric losses, such as nitrous oxide (N_2O), oxides of N (NO_x), and ammonia nitrogen (NH_3-N). The Shaffer and Delgado (2002) framework for an environmental N-Index recommended the development of a Tier-1 tool able to conduct expeditious assessments of N management practices on N losses. If the need for a deeper more complex analysis arises, an N simulation model could be used as a Tier-2 or Tier-3 tool.

Delgado et al. (2006) developed a "new" N-Index Tier-1 spreadsheet tool (NIT-1), which is qualitative in rankings. However, it is based on annual quantitative N and water balances conducted in a Windows Excel©environment to keep track of inputs and outputs and facilitate a connection to the new Windows©Nitrate Leaching and Economic Analysis Package (NLEAP, Shaffer et al., 1991) and established P-Indexes. Therefore, Delgado et al. (2006) calls the NIT-1 "new" due to three modifications: (1) expanded and combined information, (2) ability for international input, and (3) ease of use while connecting to P-Indexes and N simulation models. Our objective was to evaluate potential use of the NIT-1 to conduct prompt assessments of management practices on N dynamics and transport; testing the tool against published N loss data annually via leaching, runoff, and atmospheric pathways.

1.1. NIT-1 inputs

The NIT-1 has a combination of inputs and a large number of drop-down menus that facilitate information entry and/or help. There are also several help screens, where users can quickly assess information related to the NIT-1 entries. A user can complete the NIT-1 inputs in 5–10 min. Inputs are categorized by site, soil, crop, manure, fertilizer, irrigation, precipitation, and off-site factors.

In the site input screen, the user needs to enter date, field location (address or town), and location name.

In the soil input screen, the user needs to enter in 0–0.3 m for the surface soil horizon, percentage of soil organic matter, bulk density, and NO_3-N and ammonium nitrogen (NH_4-N) concentrations. Additionally, the concentrations of NO_3-N, NH_4-N, and the bulk densities for two additional soil depths can be entered in up to a soil depth of 1.5 m. The soil hydrologic group is selected from a drop-down menu.

In the crop input screen, the user selects the crop specifics from a drop-down menu. The yield. The user can enter up to three crops per year and three crop residues per entry. The crop and crop residue carbon to nitrogen ratio (C/N) from the previous year are also selected from a drop-down menu, and the last year's quantity of crop residue biomass needs to be entered.

The user needs to also rank the type of cropping system by the rooting depth system used (Table 1). The user's choices are: (1) deeper rooted crop rotation with average rooting depths of about 1.5 m, (2) 1 year of shallower rooted crops with average root depths lower than 0.45 m in rotation with 1 year of deeper rooted crop with rooting depths ranging from 0.9 to 1.5 m, (3) crop rotations that have average rooting depths ranging from 0.45 to 0.9 m, (4) rotations of two shallower crops with average rooting depths of <0.45 m and one deeper rooted crop, and (5) rotation of continual shallower-rooted crops with average rooting depths of less than 0.45 m depth (Table 1).

The classification of the effects of rooting depths is in agreement with Delgado (1998, 2001), Shaffer and Delgado (2002), Wu et al. (2005), and Berry et al. (2005), who recommend using rooting depths as a management factor for a new N-Index. It has been reported that commercial, shallower-rooted crops are more susceptible to NO_3-N leaching than commercial operations with deeper-rooted crops; deeper-rooted crops can even mine and recover NO_3-N from underground irrigation waters (Delgado, 1998, 2001).

In the manure input screen, the user needs to select the type of manure, method of application, and the quantity applied from a drop-down menu. The user needs to choose from the drop-down menu if the NIT-1 will use its default values for: (1) dry matter percentage, (2) kg N dry tonnes^{-1}, (3) kg NH_4-N dry tonnes^{-1}, and (4) percentage of mineralized N during the first year. If manure was applied in the previous year, the site-specific values should be used as inputs, and the user needs to answer the previous set of questions.

In the N fertilizer input screen, the user needs to enter the kg N fertilizer ha^{-1} year^{-1} applied and select from a drop-down menu whether all the fertilizer was applied once or if it was split into more than one application. The user then needs to rank the fertilizer management practices (Table 1). The user's choices are: (1) no fertilizer applied, (2) fertilizer applications follow state recommendations, (3) applications of 10–15% over state N recommendations, (4) applications of 15% over state N recommendations, and (5) applications of 25% over state recommendations (Table 1). It is expected that a trend in higher NO_3-N available to leach with respect to over-application of N will occur, which is in agreement with the results from Bock and Hergert (1991).

The user needs to select from a drop-down menu if N fertilizer applied is susceptible to NH_3-N volatilization. The type of N fertilizer, soil pH, and/or method of application with respect to climate, precipitation, or irrigation events during and after fertilizer applications needs to be selected from drop-down menus.

The user needs to rank management practices at the site with respect to NH_3-N volatilization (Table 1). The user's choices are: (1) no N fertilizer susceptible to NH_3-N volatilization was applied, (2) the N fertilizer susceptible to NH_3-N volatilization was placed with planters deeper than 5 cm, (3) the N fertilizer susceptible to NH_3-N volatilization was incorporated in less than 2 days after application or irrigation was applied immediately after N fertilizer application, (4) incorpo-

Table 1 – Nitrogen-Index Tier-1 (NIT-1 from Delgado et al., 2006)

Site characteristic	None or very low 0	Low 2	Medium 4	High 6	Very high 8	Nitrate leaching	Surface transport	Air quality
N susceptible volatization method	None applied	Placed with planter deeper than 5 cm	Incorporated<2 days after application or irrigation immediately after application	Incorporated or irrigation more than 7 days after application	Surface application without irrigation			
Column factor	0	2	4	6	8			X
Proximity of nearest field edge to named stream or lake	Very low >305 m	Low 152–305 m	Medium 61–152 m	High 9–61 m	Very high <9 m			
Column factor	0	2	4	6	8		X	
Rooting depths and crop rotation	1.5 m and deeper rooted crop rotation	0.9–1.5 m deeper rooted crop and rotation with shallower crops	0.9–1.5 m	<0.45 m and rotation with deep rooted crop	<0.45 m and no deep rooted crops in rotation			
Column factor	0	2	4	6	8		X	
Aquifer leaching potential risk (ALPR)	Very low	Low	Medium	High	Very high			
Column factor	0	2	4	6	8	X		
Tile drainage	No tile drainage	Mitigate but with pumping wetland, wood chips, and >3048 m to water body	Same as low >305 m	Same as low but <305 m to water body to water body	Drains to ditch, creek, or stream and no mitigation			
Column factor	0	2	4	6	8	X		
NH_3 volatization	Very low NH_3 volatization <22.4 kg N ha^{-1}	Low NH_3 volatization >22.4 < 33.6 kg N ha^{-1}	Medium NH_3 volatization >33.6 < 56 kg N ha^{-1}	High NH_3 volatization >56 < 84 kg N ha^{-1}	Very high NH_3 volatization >84 kg N ha^{-1}			
Column factor	0	2	4	6	8			X
Denitrification	Very low denitrification <28 kg N ha^{-1}	Low denitrification >28 < 56 kg N ha^{-1}	Medium denitrification >56 < 84 kg N ha^{-1}	High denitrification >84 < 112 kg N ha^{-1}	Very high denitrification >112 kg N ha^{-1}			
Column factor	0	2	4	6	8			X
Soil erosion (wind and water)	Very low <2.2 Mg ha^{-1}	Low 2.2–6.7 Mg ha^{-1}	Medium 6.7–11.2 Mg ha^{-1}	High 11.2–33.6 Mg ha^{-1}	Very high >33.6 Mg ha^{-1}			
Column factor	0	2	4	6	8		X	
Runoff class	Very low or negligible	Low	Medium	High	Very high			
Column factor	0	2	4	6	8		X	
Irrigation erosion	Not irrigated or furrow irrigated	Tail water recovery or QS < 6 for very erodible soils or QS < 10 for resistant soils	QS > 10 for erosion resistant soils	QS > 10 for erodible soils	QS > 6 for very erodible soils			
Column factor	0	2	4	6	8		X	
Vegetative buffer	>30.5 m wide	19.8–30.5 m wide	6.1–19.8 m wide	<6.1 m wide	No buffer			
Column factor	0	2	4	6	8		X	
Subtotal nitrate leaching component	0–10	>10–22	>22–33	>33–45	>45–56			
Subtotal surface transport component	0–7	>7–15	>15–28	>28–34	>34–40			
Subtotal air atmospheric component	0–7	>7–15	>15–22	>22–28	>28–32			
Total index points	0–24	>24–52	>52–83	>83–107	>107–128			
N hazard class	None or very low	Low	Medium	High Very high				

* Water leaching Index, nitrogen available to leach, estimated nitrate leaching, and nitrogen budget use method not shown in Table 1 (See Delgado et al., 2006 for details).

ration of N fertilizer or irrigation was employed more than 7 days after application, and (5) the N fertilizer susceptible to NH_3-N volatilization was surface applied without irrigation (Table 1). These rankings in N management with respect to potential N losses due to NH_3-N volatilization are in agreement with Meisinger and Randall (1991).

The user then needs to select from a drop-down menu if the NIT-1 with default value coefficients for NH_3-N volatilization or if site-specific NH_3-N volatilization coefficients will be used as inputs. Immediately after the entries are completed, the NIT-1 calculates and ranks the NH_3-N volatilization losses (Table 1).

The user also needs to select from a drop-down menu if the NIT-1 with default value coefficients for denitrification or if site-specific denitrification coefficients will be used as inputs. The user then needs to select from a drop-down menu the range of soil organic matter and the drainage class that is present. Immediately after the entries are completed, the NIT-1 tool will calculate and rank the denitrification losses (Table 1).

In the irrigation input screen, the user needs to select from a drop-down menu if irrigation was employed and the type that was possibly employed. The irrigation amount applied and irrigation water inorganic NO_3-N concentration needs to be entered. If there is organic N in the irrigation water, its concentration and expected annual release (%) of N from organic N needs to be entered. For additional information about irrigation systems tested, review Tarkalson et al. (2006) and Li et al. (2007).

In the precipitation input screen, the total annual precipitation during the growing season and non-growing season needs to be entered. Annual N atmospheric wet and dry deposition also needs to be entered.

In the off-site factors input screen, the NIT-1 will calculate the Annual Leaching Risk Potential Index according to Pierce et al. (1991). The user needs to use drop-down menus to select the NO_3-N leaching range, NO_3-N travel time, and the position and vulnerability of the aquifer required for the Annual Leaching Risk Potential Index.

The user then needs to rank the proximity of the field edge to streams or lakes. The user's choices are: (1) 305 m, (2) 152–305 m, (3) 61–152 m, (4) 9–61 m, and (5) <9 m (Table 1). This is in agreement with Flynn et al. (2000).

The user also needs to rank the type of buffer design. The user's choices are: (1) 30.5 m wide or precision conservation buffers, (2) 19.8–30.5 m wide, (3) 6.1–19.8 m wide, (4) <6.1 m wide, and (5) no buffer (Table 1). This is in agreement with Dosskey et al. (2005) and Flynn et al. (2000).

The user then needs to rank the soil runoff class. The user's choices are: (1) very low or negligible, (2) low, (3) medium, (4) high, and (5) very high (Table 1). This is in agreement with Flynn et al. (2000).

The user's final step is to rank the type of irrigation erosion. The user's choices are: (1) not irrigated or furrow irrigation, (2) tail water recovery or QS (Q = flow rate of water; S = furrow slope) lower than 6 for very erodible soils or QS < 10 for resistant soils, (3) QS greater than 10 for erosion resistant soils, (4) QS greater than 10 for erodible soils, and (5) QS greater than 6 for very erodible soils (Table 1). This is in agreement with Flynn et al. (2000).

1.2. NIT-1 algorithms for sources and pathways

Although the NIT-1 is qualitative in rankings, it is based on quantitative N balances that track sources of N and pathways for N removal, which is similar to the annual N-Index of Pierce et al. (1991) that was included in the DOS version of the NLEAP model (Shaffer et al., 1991). The NIT-1 has several help screens and a large number of drop-down help menus, which users can quickly access for interpretation of results and recommendations due to results.

The NIT-1 keeps track of inorganic N sources, such as the N fertilizer, initial soil NO_3-N, initial soil NH_4-N, NH_4-N from manures, irrigation NO_3-N, and atmospheric N deposition inputs. Additionally, the NIT-1 assesses N transformations, such as mineralization of N from crop residues, organic soil matter, and other organic sources that contribute to N. Eq. (1) is used to sum all of the N inputs for the system.

$$S_{NI} = N_f + N_{in} + N_{min} + N_{atm} + N_{ma1} + N_{ma2} + N_{cr} + N_{irb} + N_{iro} \tag{1}$$

where:

S_{NI} = total system nitrogen inputs (kg N ha^{-1} year^{-1});
N_f = N applied as fertilizer (kg N ha^{-1});
N_{in} = root zone initial inorganic N before planting (0–1.5 m depth or 0 – depth of the deepest rooted crop – kg NH_4-N + NO_3-N ha^{-1});
N_{min}[1] = mineralization of N from soil organic matter (0–0.3 m depth; kg N ha^{-1} year^{-1});
N_{atm} = atmospheric N deposition (kg N ha^{-1} year^{-1});
N_{ma1}[2] = initial NH_4-N + N mineralization from manure kg N ha^{-1} year^{-1};
N_{ma2}[2] = N mineralization from manure applied last year kg N ha^{-1} year^{-1};
N_{cr} = crop residue N mineralization (kg N ha^{-1});
N_{irb} = background NO_3-N applied in irrigation water (kg NO_3-N ha^{-1});
N_{iro} = available organic N applied in irrigation water (kg N ha^{-1}).

The NIT-1 also factors in the Meisinger and Randall (1991) impacts and effects yielded from fertilizer, management, and soil pH on NH_3-N volatilization losses. Table 2 shows the NIT-1 NH_3-N volatilization coefficients using a matrix of fertilizer types and management adapted from Meisinger and Randall (1991). Immediately after the entries are completed, the NIT-1 calculates and ranks the NH_3-N volatilization losses using Eq. (2) (Table 1). The user needs to choose from a drop-down menu if the NIT-1 will use the NH_3-N volatilization coefficients or if the NH_3-N volatilization site-specific coefficients will be used.

[1] The NIT-1 default value for organic soil matter N mineralization is 45 kg N ha^{-1} per 1% soil organic matter (Vigil et al., 2002); users can enter site-specific rate.

[2] The NIT-1 default value for manure or compost N content is from Davis et al. (2002), and the mineralization rates are from Eghball et al. (2002); users can enter site-specific content values and site-specific rates.

Table 2 – Nitrogen-Index Tier-1 (NIT-1) matrix for ammonia volatilization coefficients due to climate and type and management of N fertilizer applied

Type of fertilizer	Management of fertilizer	Weather		
		Humid	Sub-humid	Dry
Urea	Surface applied	10	15	25
Urea	Incorporated	2	3	5
$(NH_4)_2SO_4$	Surface applied	4	8	15
$(NH_4)_2SO_4$	Incorporated	1	1	2
NH_4NO_3	Surface applied	2	4	10
NH_4NO_3	Incorporated	0	5	1
Anhydrous-NH_3	Incorporated	1	2	3

Adapted from Meisinger and Randall (1991).

$$N_v = (N_{fsv} \cdot N_{vcf}) + (N_{msv} \cdot N_{vcm}) \quad (2)$$

where:

N_v = N ammonia volatilization (kg NH_3-N ha^{-1});
N_{fsv} = N fertilizer susceptible to NH_3-N volatilization (kg N ha^{-1});
N_{msv} = NH_4-N from organic inputs susceptible to NH_3-N volatilization (kg N ha^{-1});
Nvcf = N ammonia volatilization coefficient fertilizer.
Nvcm = N ammonia volatilization coefficient manure.

The NIT-1 factors in the Meisinger and Randall (1991) impacts of drainage and organic soil matter while assessing denitrification. Table 3 shows the NIT-1 denitrification coefficients using a matrix of drainage and soil organic matter content adapted from Meisinger and Randall (1991). The user needs to choose from a drop-down menu if the NIT-1 will use the denitrification coefficients or if the site-specific denitrification coefficients will be used. Immediately after the entries are completed, the NIT-1 calculates and ranks the denitrification losses using Eq. (3) (Table 1).

$$N_d = (N_f + N_{iNO_3\text{-}N} + N_{mi} - N_v) \cdot N_{dc} \quad (3)$$

where:

N_d = N denitrification (kg N ha^{-1});
N_f = N applied as fertilizer (kg N ha^{-1});
$N_{iNO_3\text{-}N}$ = surface 0–0.3 m initial kg NO_3-N ha^{-1};
N_{mi} = inorganic N added with organic inputs (kg N ha^{-1});
N_v = N ammonia volatilization (kg NH_3-N ha^{-1}; Eq. (2));
N_{dc} = N denitrification coefficient.

The user also needs to rank the total erosion (wind and water) at the site (Table 1). The user's choices are: (1) less than 2.2 Mg ha^{-1}, (2) from 2.2 to 6.7 Mg ha^{-1}, (3) from 6.7 to 11.2 Mg ha^{-1}, (4) from 11.2 to 33.6 Mg ha^{-1}, and (5) greater than 33.6 Mg ha^{-1} (Table 1). This is in agreement with Flynn et al. (2000). The NIT-1 will estimate the N off-site transport by multiplying the mean soil erosion by the soil organic matter content, by the soil organic C content (0.58) and then, by the soil organic N content (0.125) (Eq. (4)). The user needs to choose from a drop-down menu if the NIT-1 will use the soil organic C and N content values, or if the C and N content site-specific values will be used.

$$N_{er} = \frac{SOM}{100} \cdot ER \cdot 0.58 \cdot 0.125 \quad (4)$$

where:

N_{er} = N erosion (kg N ha^{-1});
SOM = soil organic matter (%);
ER = erosion rate (kg ha^{-1}).

The NIT-1 will estimate the available N lost, due to off-site transport, by multiplying the mean N lost to erosion (N_{er}) by a constant (k_{er}) reflecting available N Eq. (5). The user needs to choose from a drop-down menu if the NIT-1 will use the constants of 0.10 and 0.15 for non-manure and manure treated

Table 3 – Nitrogen-Index Tier-1 (NIT-1) matrix for denitrification coefficients due to drainage and soil organic matter content

Drainage group				
Excessively well drained	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained
2	3	6	10	20
4	4	8	15	25
6	6	12	20	30

Adapted from Meisinger and Randall (1991).

sites, respectively, or if site-specific values will be used.

$$N_{erav} = N_{er} \cdot k_{er} \quad (5)$$

where:

N_{erav} = available N erosion (kg N ha^{-1});
N_{er} = N erosion (kg N ha^{-1});
k_{er} = erosion N available constant.

The NIT-1 tool keeps tracks N removal using Eq. (6) to sum N uptake by the crop and N losses other than NO_3-N leaching (denitrification, ammonia volatilization and erosion).

$$S_{NR} = N_c + N_d + N_v + N_{erav} \quad (6)$$

where:

S_{NR} = cropping system N pathways for removal (kg N ha^{-1} $year^{-1}$);
N_c = N uptake by crops (kg N ha^{-1});
N_d = N denitrification (kg N ha^{-1}; Eq. (3));
N_v = N ammonia volatilization (kg NH_3-N ha^{-1}; Eq. (2));
N_{erav} = N erosion (kg N ha^{-1}; Eq. (5)).

The NIT-1 calculates the NAL using Eq. (7). The program will infer that the differences between N sources and losses will be mineralized and available as NO_3-N. Immediately after the entries are completed, the NIT-1 tool calculates and ranks the NAL using Eq. (7) (Table 1).

$$NAL = S_{NI} - S_{NR} \quad (7)$$

where:

NAL = NO_3-N available to leach (kg NO_3-N ha^{-1});
S_{NI} = cropping system nitrogen inputs (kg N ha^{-1} $year^{-1}$; Eq. (1));
S_{NR} = cropping system N pathways for removal (kg N ha^{-1} $year^{-1}$; Eq. (6)).

Immediately after the precipitation and soil hydrologic group inputs are entered, the NIT-1 calculates and ranks the Williams and Kissel (1991) LI values as very low, low, medium, high, and very high (Table 1). Immediately after the entries are computed, the NIT-1 calculates and ranks NO_3-N leaching losses using Eq. (8) (Pierce et al., 1991).

$$NL = NAL \times (1.0 - \exp^{(-k \times WAL/POR)}) \quad (8)$$

where:

NL = NO_3-N leaching (kg NO_3-N ha^{-1} $year^{-1}$) at specific depth (e.g. root zone);
NAL = NO_3-N available to leach (kg NO_3-N ha^{-1} $year^{-1}$ Eq. (7));
k = is a coefficient (1.2);
WAL = water available for leaching (it can be the LI for an annual NAL);
POR = soil porosity [(1 − (bulk density/particle density)) × (leaching depth × unit area)].

The NIT-1 tool keeps tracks of total N removal using Eq. (9) to sum cropping system N pathways for removal Eq. (6) plus NL Eq. (8).

$$S_{TNR} = S_{NR} + NL \quad (9)$$

where:

S_{TNR} = cropping system total N pathways for removal (kg N ha^{-1} $year^{-1}$);
S_{NR} = cropping system N pathways for removal (kg N ha^{-1} $year^{-1}$; Eq. (6));
NL = NO_3-N leaching (kg N ha^{-1} $year^{-1}$; Eq. (8)).

The NIT-1 calculates residual soil NO_3-N on an annual basis using Eq. (10). The program will subtract the cropping system total N pathways for removal Eq. (9) from the total system nitrogen inputs Eq. (1).

$$RN_{NO_3\text{-}N} = S_{NI} - S_{TNR} \quad (10)$$

where:

$RN_{NO_3\text{-}N}$ = residual soil NO_3-N (kg NO_3-N ha^{-1} $year^{-1}$);
S_{NI} = total system nitrogen inputs (kg N ha^{-1} $year^{-1}$; Eq. (1));
S_{TNR} = cropping system total N pathways for removal (kg N ha^{-1} $year^{-1}$; Eq. (9)).

The NIT-1 will calculate the N use efficiency for the cropping system by dividing the N-crop content, divided by the system nitrogen inputs Eq. (11).

$$S_{NUE} = \frac{N_c}{S_{NI}} \cdot 100 \quad (11)$$

where:

S_{NUE} = cropping system N use efficiency (%);
N_c = N uptake by crop (kg N ha^{-1} $year^{-1}$);
S_{NI} = total system nitrogen inputs (kg N ha^{-1} $year^{-1}$; Eq. (1)).

One advantage of having an Excel Windows NIT-1 environment is that in a few minutes (<10 min), the user can print a one page N-Index where the leaching, surface, and air quality factors are ranked. A second page with flag screens (graphs) and recommendations can be printed if needed (Delgado et al., 2006). There is the potential to set up the NIT-1 to print site-specific recommendations by regions, soils, crops, hydrologic groups, and other site-specific information. The NIT-1 annual precipitation, soil properties, and management information can be exported or moved into the NLEAP, since they are connected. Additionally, Delgado et al. (2006) reported that the NIT-1 is connected to the P-Index allowing for simultaneous evaluations of both nutrients.

Table 4 – Sites used to test the Nitrogen-Index Tier-1 (NIT-1) with observed values for the N loss components pathways

Site	Crop	Component (observed)	Treatments	Period	Source
Alabama	Cotton rye	Runoff	Tillage	1984–1989	Soileau et al. (1994)
Argentina	Corn	Denitrification NH_3 volatilization	N fertilizer rate	1994–1999	Rozas et al. (1999, 2001)
China	Corn–winter wheat	NO_3-N leaching	N fertilizer rate	2001–2004	Li et al. (2007)
Ohio	Corn	NO_3-N leaching	N fertilizer rate tillage	1971–1975	Chichester (1977)
Nebraska	Corn	NO_3-N leaching	Manure rates	2002–2003	Tarkalson et al. (2006)
New York	Corn	NO_3-N leaching	N fertilizer rate	1992–1994	Sogbedji et al. (2000, 2001)

The majority of the observed data was selected to report from lysimeters for a period of least 1 full year that has NH_3-N volatilization, denitrification and/or runoff for a long period to allow for a more complete test.

2. Materials and methods

2.1. *NIT-1 tested against N loss pathways (published data)*

Shaffer and Delgado (2002) and Delgado et al. (2006) recommend that the N-Index should be used to assess the effects of N management practices on N losses on at least an annual basis. Our main objective was to test NIT-1 against actual data that have been collected on N loss pathways. We searched available literature and found that there are few complete data sets that monitor N losses for NO_3-N leaching, denitrification (N_2), NH_3-N volatilization, and surface erosion N loss pathways over a full year period including the growing and non-growing seasons. Thompson and Meisinger (2002, 2004) also acknowledge the lack of this kind of data in the US for NH_3-N volatilization. We selected studies that assess field N losses on a whole year basis or during a long-term period. Studies were only selected if the authors monitored the field losses for at least 2 years. This unique data set includes studies from Alabama, Argentina, China, Nebraska, New York, and Ohio (Table 4).

The studies covered a wide range of climates, soils, and hydrological cycles. The Nebraska study monitored the effects of different rates of manure applications on NO_3-N leaching losses during a 2-year period. Other studies monitored the effects of N fertilizer rates and tillage on N loss pathways (Table 4). General information is presented in Table 4. For additional details, please review Chichester (1977), Rozas et al. (1999, 2001), Sogbedji et al. (2000, 2001), Soileau et al. (1994), Tarkalson et al. (2006) and Li et al. (2007).

NIT-1 enables the depth to be set where the NO_3-N leaching will be evaluated. To be able to compare NIT-1 NO_3-N leaching losses to the observed NO_3-N leaching losses from lysimeters, we set the NO_3-N leaching depths similar to the depths of the lysimeters used at each specific site. The depths for leaching were set at 2.44, 2.1, and 0.9 m depths for the Ohio, Nebraska, and New York lysimeters, respectively. The management information from each study was entered into the NIT-1 tool and the NIT-1 loss outputs were promptly compared to the measured N loss pathways. Correlations were made using SAS REG (SAS Inc., 1988). The intercept (b_0) and slope (b_1) was tested with SAS REG for values that differed from 0 to 1, respectively.

2.2. *NIT-1 tested against observed and simulated residual soil NO_3-N and against simulated NO_3-N leaching (published data)*

We randomly selected studies conducted at some of our national and international cooperative sites located in Argentina, China and Northeastern and South Central Colorado (Table 5). Basic information about these sites is

Table 5 – General information for Argentina and USA sites, NLEAP and N-Index Tier-1 (NIT-1) Annual Leaching Risk Potential[a], and NIT-1 rankings

Country	Site #	Year	Crop[b]	N rate kg N ha^{-1}	NLEAP ALRP[a]	NIT-1 ALRP[a]	NIT-1 ranking
Argentina	1	2000	Corn	160	M	M	L
Argentina	2	2001	Corn	158	VL	VL	L
Argentina	3	2000	Corn	112	M	M	L
USA	4	2000	Corn	246	VH	H	M
USA	5	2000	Corn	246	VH	H	M
USA	6	2000	Corn	246	VH	H	M
USA	7	2000	Corn	134	VH	M	L
USA	8	1994–1995	WCR	0	H	M	VL
USA	9	1994–1995	WCR	0	H	M	VL
USA	10	1994	Potato	231	VH	H	L
USA	11	1995	Potato[c]	246	VH	M	L
USA	12	1994	Barley	41	H	M	L
USA	13	1994	Potato[d]	140	VH	M	M

[a] Class: VL, very low; L, low; M, medium; H, high; VH, very high.
[b] Crop: Corn (*Zea mays* L.), WCR: winter cover rye (*Secale cereale* L.), potato (*Solanum tuberosum* L.), and barley (*Hordeum vulgare* L.).
[c] Tonnes of winter cover rye crop residue (21 Mg ha^{-1}).
[d] Tonnes of compost (22 Mg ha^{-1}).

presented in Table 5. For detailed additional information about South Central Colorado sites, see Delgado et al. (1998, 2000, 2001a,b) and Delgado (2001); for Northeastern Colorado, see Delgado and Bausch (2005); for Argentina, see Rimski-Korsakov et al. (2004) and for China see Li et al. (2007). For Argentina, China and Northeastern Colorado, initial and final soil NO_3-N after harvest was measured between 0 and 1.5 m depths. For South Central Colorado, with shallower, gravelly soils, we measured soil NO_3-N between 0 and 0.9 m depths.

The NIT-1 inputs were entered for each site and saved with different file names. Data from each site, such as dates of planting, yields, N fertilizer amounts and time of applications, weather data, irrigation, precipitation, air temperature, and all additional data were entered in the NLEAP. For this study, we used the NLEAP DOS version (Shaffer et al., 1991; Delgado et al., 1998). The NLEAP model was run on an annual basis (12 months) from the initial month of planting. The same data were used for the NIT-1.

Correlations were made using SAS REG (SAS Inc., 1988). The intercept (b_0) and slope (b_1) was tested with SAS REG for values that differed from 0 to 1, respectively. Correlations tested were: (1) the NIT-1 residual soil NO_3-N in relation to NLEAP residual soil NO_3-N on an annual basis, (2) the NIT-1 residual soil NO_3-N in relation to observed residual soil NO_3-N after harvest, (3) NIT-1 NO_3-N leaching in relation to NLEAP NO_3-N leaching, (4) NIT-1 denitrification in relation to NLEAP denitrification, and (5) NIT-1 NH_3 volatilization in relation to NLEAP NH_3 volatilization.

2.3. *NIT-1 sensitivity analysis*

Site ten, a potato (*Solanum teberosum* L.) crop grown on a sandy loam site, was selected at random to conduct a sensitivity analysis. Sensitivity analyses were conducted for site 10 by adding an imaginary precipitation event on July 30, when the potato was fully grown and there was full canopy. For July 30, we conducted simulations with imaginary precipitation events measuring 50, 125, and 254 mm, which left all other factors equal. The effects of these imaginary irrigation/precipitation events on N pulses due to NO_3-N leaching, denitrification, and on residual soil NO_3-N were evaluated. The same steps were repeated using information at site ten, however the soil properties were changed to simulate a sandy clay loam texture.

3. Results and discussion

3.1. *Correlations of NIT-1 results versus actual data on N loss pathways*

The NIT-1 assessments, when compared to actual N loss pathways data, illustrated significant correlations ($P < 0.001$; Fig. 1). The NIT-1 assessment of N loss pathways for NO_3-N leaching, denitrification, NH_3-N volatilization, and erosion was correlated with observed values (Fig. 1). The intercept (b_0) and slope (b_1) values did not differ significantly from 0 to 1, respectively. These data suggest that the annual NIT-1 assessment was similar to measured values (Fig. 1).

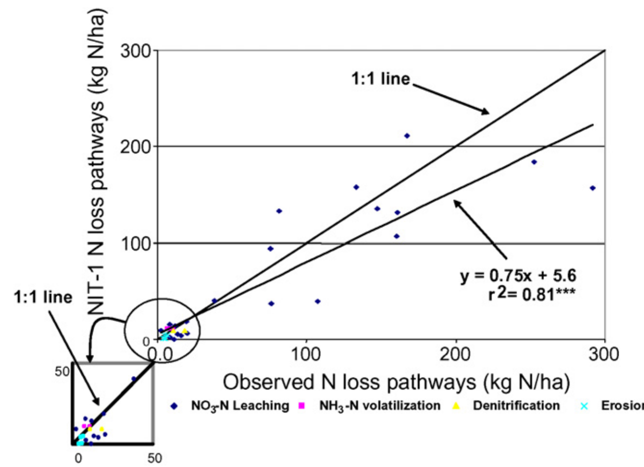

Fig. 1 – Nitrogen-Index Tier-1 (NIT-1) N loss pathways versus observed values from studies sites located in Alabama, Argentina, China, Ohio, Nebraska and New York. Selected sites were observations collected on an annual basis and/or for extensive periods ($^{***}P < 0.001$).

The NIT-1 and observed NO_3-N leaching values were in agreement with long-term study that monitored the effects of rates of manure applications (Table 4 and Fig. 1). The highest mechanism for N losses was the NO_3-N leaching pathways. Although the NIT-1 was able to correlate with this set of studies, there is the need to conduct future studies, so all of the N loss pathways can be measured for the same management practices over a long-term study (3–5 years). As these studies become available, newly developed tools, such as the NIT-1, could be extensively tested under different management scenarios for different agroecosystems located in the US. Thompson and Meisinger (2002, 2004) also reported on the need for additional NH_3-N loss studies. They reported that the volatilization of spring applied slurry could be as high as 70%. We added a footnote to the NIT-1 to make users aware of the recent discoveries from Thompson and Meisinger (2004).

The NIT-1 performed in accordance with the general trend for N loss pathways. The NIT-1 quick spreadsheet tool approach is the type of tool that nutrient managers and conservationists need to conduct fast and effective assessments of the effects of management practices on N loss pathways.

3.2. *Correlations of NIT-1 results versus actual and simulated data on residual soil NO_3-N and simulated NO_3-N leaching*

The NIT-1 residual soil NO_3-N was correlated with a NLEAP simulation of residual soil NO_3-N on an annual basis (Fig. 2a; $P < 0.001$). The intercept (b_0) and slope (b_1) was not significantly different from 0 to 1 ($P < 0.001$; Fig. 2a). The NIT-1 residual soil NO_3-N values were correlated with observed residual soil NO_3-N values after harvest (Fig. 2b; $P < 0.001$). The intercept (b_0) and slope (b_1) values did not significantly differ from 0 to 1 ($P < 0.001$; Fig. 2b), respectively. This suggests that there was not significant NO_3-N leaching during the winter periods at these sites. The NIT-1 and NLEAP NO_3-N leaching was correlated (Fig. 3; $P < 0.001$). The NIT-1 assessment of the Annual

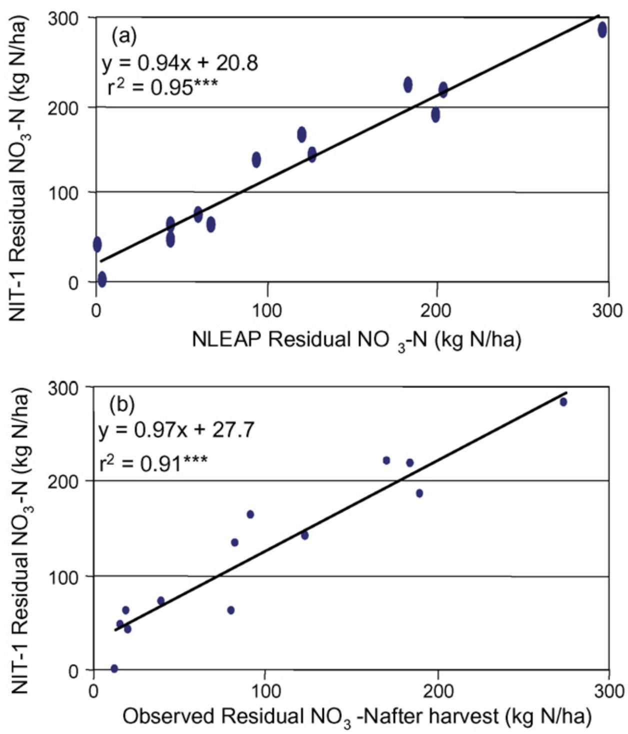

Fig. 2 – Nitrogen-Index Tier-1 (NIT-1) residual NO_3-N versus NLEAP simulated residual NO_3-N on an annual basis (a) and observed residual NO_3-N (b) for Argentina, and USA sites ($^{***}P < 0.001$).

Leaching Risk Potential Index was in close agreement with the NLEAP Annual Leaching Risk Potential Index (Table 5).

3.3. *Sensitivity analysis*

We conducted a sensitivity analysis to see how susceptible the NIT-1 is to precipitation events. We found that the NIT-1 is not sensitive to large precipitation events of rain for a silty clay loam (Fig. 4). Events of 50 mm assessed with NLEAP and the NIT-1 gave similar results (Fig. 4). However, a 125 mm event, assessed with NLEAP, reduced the residual soil NO_3-N and increased denitrification and NO_3-N leaching losses (Fig. 4). With 125 mm of precipitation, the NLEAP residual soil NO_3-N was reduced by 32 kg N ha^{-1}, which is mainly due to 31 kg NO_3-N ha^{-1} that increased in NO_3-N leaching (Fig. 4). The net NLEAP denitrification was reduced by 7 kg NO_3-N ha^{-1} in silty clay loam, since the higher 31 kg NO_3-N ha^{-1} of leaching reduces the mass of available NO_3-N to denitrification. The NIT-1 is not as responsive to these pulse changes in precipitation that contribute to the lower residual soil NO_3-N value (14 kg NO_3-N ha^{-1}, for the silty clay loam, Fig. 2). The NIT-1 NO_3-N leaching losses were increased by 14 kg NO_3-N ha^{-1}, for the silty clay loam (Fig. 2).

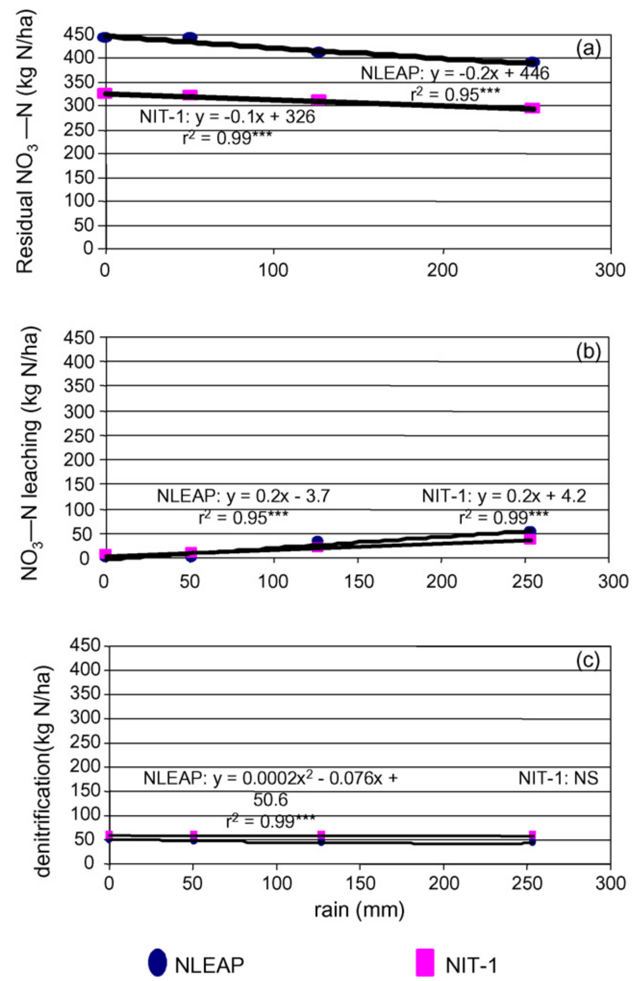

Fig. 4 – Sensitivity analysis of the Nitrogen-Index Tier-1 (NIT-1) and NLEAP residual soil NO_3-N (a); NO_3-N leaching (b); denitrification (c) for a silt clay loam due to a rain event ($^{***}P < 0.001$).

A similar sensitivity analysis with a coarser sandy soil showed more drastic changes (Fig. 5). A 50 mm precipitation event in the sandy soils during the middle of the growing season with closed canopy significantly contributed to a loss of about 102 kg NO_3-N ha^{-1} leached out (NLEAP), while the NIT-1 is not sensitive to such a storm event (13 kg NO_3-N ha^{-1}). A 50 mm irrigation or precipitation event in the sandy soil reduced the residual soil NO_3-N by about 105 kg NO_3-N ha^{-1}, while the NIT-1 was not sensitive and only reduced the residual soil NO_3-N by about 14 kg NO_3-N ha^{-1} (Fig. 5).

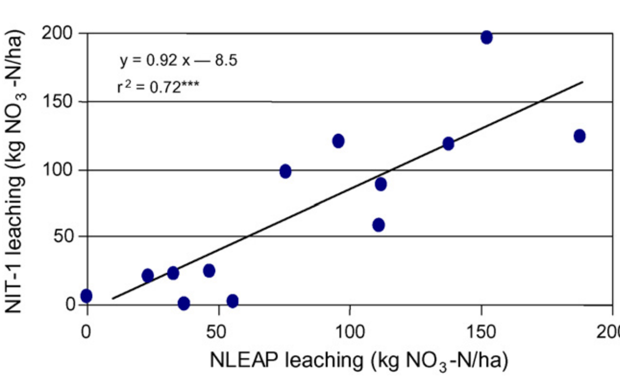

Fig. 3 – Nitrogen-Index Tier-1 (NIT-1) NO_3-N leaching losses versus NLEAP simulated values for Argentina, and USA sites ($^{***}P < 0.001$).

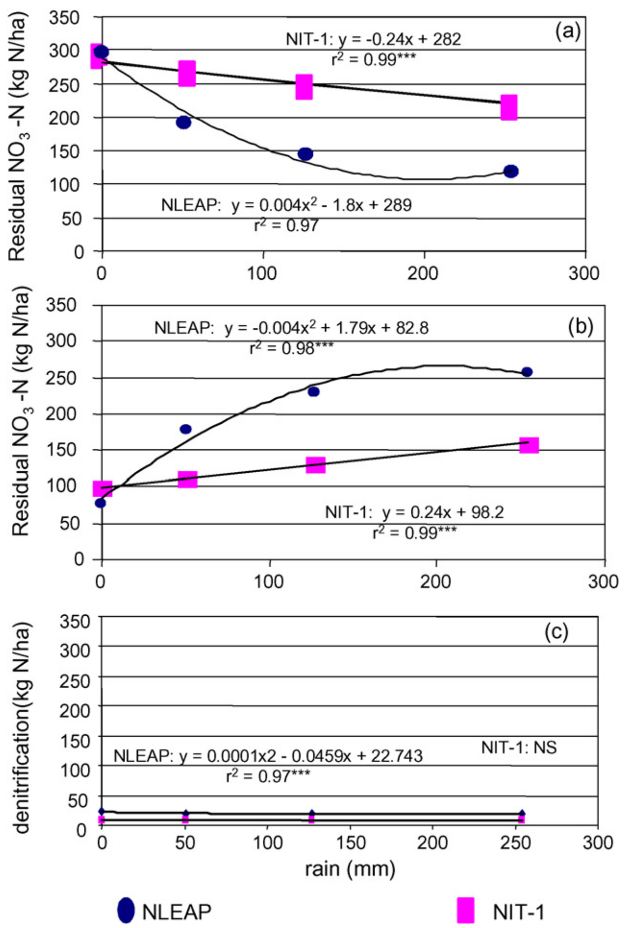

Fig. 5 – Sensitivity analysis of the Nitrogen-Index Tier-1 (NIT-1) and NLEAP residual soil NO_3-N (a); NO_3-N leaching (b); denitrification (c) for a sandy soil due to a rain event ($^{***}P < 0.001$).

The NIT-1 accounted for different irrigation systems (sprinkler, furrow, etc.) used across these sites and for different climates and agricultural systems (e.g. Argentina, China, Ohio, New York). If needed, there is the potential to calibrate and validate the NIT-1 for new irrigation systems or management scenarios not tested in this set of data (Table 4). The N-Index accounted for ecological principles of using buffers, deeper rooted systems, distance to water bodies and other off-site parameters.

4. Conclusions

The NIT-1 should be used with an awareness of its potential limitations. The sensitivity analysis showed that the N loss pathways are very sensitive to pulse events. However, the evaluation of NIT-1 against annual measured values across several regions of the US and other countries shows that the NIT-1 is overall effective at estimating the N loss pathways on an annual basis ($P < 0.001$; Fig. 1). We recommend that in order to improve the performance of NIT-1, users should calibrate and validate NIT-1 to their specific region. Even computer models, such as NLEAP, have limitations and need to be calibrated to regions and/or areas (Shaffer and Delgado, 2001).

We suggest that there is potential to calibrate the NIT-1 denitrification and NH_3-N volatilization coefficients for a set of site-specific management practices with hydrological group combinations. We propose that we can use models to calibrate, fit, and populate needed coefficient databases, such as denitrification and NH_3-N volatilization. One of the major advantages of the NIT-1 spreadsheet approach is that it is based on published information from Meisinger and Randall (1991), Vigil et al. (2002), Davis et al. (2002), and Eghball et al. (2002). However, users can enter site-specific content values and site-specific rates to improve the NIT-1 tool.

There were significant correlations between the NIT-1 and the NLEAP in assessing residual soil NO_3-N and NO_3-N leaching. Additionally, the assessment of the Annual Leaching Risk Potential Index from Pierce et al. (1991) was in close agreement. The NIT-1 air N losses were equated with the NLEAP simulated values. The slope suggested that the NIT-1 underestimated values when predicting these atmospheric N losses. Since we had significant correlations of the NIT-1 and NLEAP in assessing residual soil NO_3-N, we suggest that the main mechanism for N losses at these sites was NO_3-N leaching. We did not associate the NIT-1 surface N transport, since NLEAP only simulates movement of soluble N in surface transport (Shaffer et al., 1991). There is the need for additional research in testing the NIT-1 in situations of higher atmospheric and off-site surface transport losses with other simulation models and/or with data measurements of atmospheric and surface transport N loss data.

Our results suggest that the NIT-1 is a potential, fast and effective nutrient management tool capable of assessing the effects of management on NO_3-N dynamics and transformations. We concluded that the NIT-1 is an effective nutrient management tool to be used for risk assessment as recommended by the framework of Shaffer and Delgado (2002). However, users need to consider and be aware of the NIT-1 limitations. The Delgado et al. (2006) NIT-1 is an adequate tool to conduct assessments of management practices on N loss pathways.

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