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Denitrification in Seepage-Irrigated Vegetable Fields in South Florida[1]

Eric H. Simonne and Benjamin Morgant[2]

Vegetable crops such as tomato (*Lycopercicon esculentum* Mill.), bell pepper (*Capsicum annuum* L.), watermelon (*Citrullus lanatus* (Thumbs.) Mat. & Nakai), summer squash (*Cucurbita pepo* L.), green bean (*Phaseolus vulgaris* L), potato (*Solanum tuberosum* L), and eggplant (*Solanum melongena* L.) are widely grown in south Florida in the winter and spring seasons. The main irrigation methods used for vegetable production are drip irrigation (also called microirrigation) and seepage irrigation (also called subirrigation or water table control) (Fig. 1). Drip irrigation consists of delivering water to each plant through a network of pipes and drip tubing. Irrigation scheduling can be precisely managed to meet crop demands and maximize crop yields and quality.

Seepage irrigation is the most common irrigation method in south Florida on muck and sandy soils, and consists of maintaining a water table perched on an impermeable layer. The top of the water table is typically maintained at between 18 and 24 inches deep. While drip irrigation has been gaining popularity in the last twenty years, seepage irrigation remains a very common production system in south Florida. In the field, the distinction between seepage irrigation and drip irrigation is not always clear, as in most cases, a perched water table is maintained in drip-irrigated fields. Because of the sandy soils low water-holding capacity, “true” drip irrigation (when all the water is provided by the drip tape) is rare in south Florida.

These vegetable crops are also grown with intensive fertilization with UF/IFAS N fertilizer recommended rates ranging from 150 to 200 lbs N/acre (Olson and Simonne, 2004). For crops grown with drip irrigation, current recommendations are to use the results of a soil test, and to apply a third to a half of the N and K, and all the P and micronutrients preplant. The remaining N and K are injected throughout the growing season. When drip irrigation is used, nutrients move with the water by gravity until the water encounters the impermeable layer. When irrigation water reaches the impermeable layer, lateral water movement occurs (Simonne et al., 2003). For crops grown with seepage irrigation, all nutrients recommended by the soil test results are applied preplant before the plastic is laid. Approximately a third of the N and K, and all the P are applied broadcast in the bed (bottom mix), and the remaining N and K are applied in 2 bands located on the bed shoulders (hot mix). In this system, water

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2. Eric H. Simonne, assistant professor, and Benjamin Morgant, short term scholar, Horticultural Sciences Department, Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, 32611.

Figure 1. Vegetable crops grown in Florida with seepage irrigation and drip irrigation; a) water moves laterally when it reaches the spodic layer on an Acona fine sand, b) holes in the plastic are made by the fertilizer injection wheel, c) water control structures, and d) cantaloupe grown with drip irrigation.

moves upward by capillarity and slowly solubilizes nutrients in the root zone. Heavy rains are common in Florida and may leach nutrients out of the root zone. A leaching rain occurs when it rains at least 3 inches in 3 days or 4 inches in 7 days (Simonne and Hochmuth, 2004). After a leaching rain, drip- and seepage-irrigated fields may become flooded. Vegetable crop growth and yield are reduced when anaerobic conditions are maintained for more than 24 hours (Rao and Li, 2003). To reduce the incidence of flooding, a network of ditches and canals conveys the water to large pumping stations that can rapidly move it out of the farmed land and into an enclosed retention area where dentrification may occur. Hence, the N fertilizer applied to vegetable fields may be taken up by the crop, denitrified (denitrification is the loss of NO_3-N under warm and anaerobic conditions), volatilized (volatilization is the loss of NH_4-N under warm and aerobic conditions), or moved off-site by leaching rains where, because water is typically pumped into an enclosed retention area, denitrification may also occur (Cockx and Simonne, 2003). Vegetable crop fertizer application rates are often greater than the UF/IFAS recommended rates to ensure adequate fertilization and economical productivity despite these possible N losses.

In response to public awareness of environmental issues, section 303(d) of the Federal Clean Water Act of 1977 (US Congress, 1977) required that states identify impaired water bodies and establish total maximum daily loads (TMDLs) for pollutants entering these water bodies. Best Management Practices (BMPs) were defined as specific cultural practices aimed at reducing the negative environmental impact of agricultural production while maintaining or increasing yield and productivity. In 1987, the Florida legislature passed the Surface Water Improvement and Management (SWIM) Act requiring the development by the five Florida water management districts, of plans to clean up and preserve Florida lakes, bays, estuaries, and rivers. The modification made in 1994 to the Florida Fertilizer Law (Florida Statutes Chapter 576) known as the Nitrate Bill (FS 576.045) established a mechanism to fund projects aiming at protecting the state's water resources by improving fertilizer management practices (Kuhl et al., 1996). In 1999, the Florida Watershed Restoration Act defined a process for the development of TMDLs. The Florida Department of Agriculture and Consumer Services released the “Water Quality/Quantity BMPs for Indian River Area Citrus Groves” in 2000 (Bowman, 2000) and the “Florida Vegetable and Agronomic Crop Water Quality and Quantity BMP Manual” in 2003 (Fla. Dept. Ag. Consum. Serv., 2004). Both manuals define the BMPs that will apply to these industries in Florida. Current nutrient BMPs focus on soil testing, plant analysis, and irrigation scheduling.

The practical impact of fertilization practices on water quality in south Florida is not fully understood. It is possible that all the N fertilizer used above the UF/IFAS recommended rate directly contributes to the degradation of water quality. It is also possible that N fertilization rates above current UF/IFAS recommendations are needed in seepage-irrigated soils (and drip-irrigated flatwood soils with naturally high water tables) to offset N loss by denitrification. However, the occurrence and rate of denitrification in vegetable fields is not known. Preservation of water quality through improved N management in vegetable production requires an understanding of the fate of N in vegetable fields, including denitrification. The objectives of this article are to

1. describe denitrification and the factors known to affect its rate,

2. present current methods available for the measurement of denitrification rate,

3. summarize available estimates of denitrification rate, and

4. attempt to provide guidelines on how to account for potential denitrification losses in fertilizer programs.

Factors Affecting Denitrification Rate

The N cycle is a set of transformations that affect N in the biosphere, by which N passes from air to soil to soil organisms and back to air. Denitrification is defined as the reduction of nitrate (NO_3) to gaseous dinitrogen (N_2) by a series of reactions in which N goes from NO_3 to NO_2 (nitrite) to NO (nitric oxide) to N_2O (nitrous oxide), and finally to N_2 (Payne, 1981). Denitrification can be described as: $4\ H^+ + 5\ (CH_2O) + 4\ NO_3^- \rightarrow 2\ N_2 + 5\ CO_2 + 7\ H_2O$, where NO_3 is in the soil solution and N_2 is a gas released into the atmosphere. The most prevalent denitrifying bacteria in soils are species of *Pseudomonas* (especially *P. fluorescens*) and *Alkaligenes* (Gamble et al., 1977), but approximately 30 genera have been confirmed to be capable of denitrification (Bryan, 1981; Tsai, 1989). In the absence of oxygen (anoxic conditions), these heterotrophic bacteria use nitrate as a terminal electron acceptor in their cellular respiration.

The main factors that affect the activity of the denitrifying bacteria are nitrate concentration (Fillery, 1983), soil organic matter content (Brettar and Hofle, 2002; Hahdel and Isermann, 1992; Tsai, 1989), moisture level (Tsai, 1989; Weir et al., 1993), oxygen concentration (Fillery, 1983), pH (Müller et al, 1980), and soil temperature (Mahli et al., 1990; Standford et al., 1975). In field conditions, these factors tend to act together, and it is often difficult to measure the specific effect of each of them. The simultaneous occurrence of favourable factors for the growth of the denitrifying bacteria will result in a bacterial population increase and a subsequent increase in denitrifying activity.

Nitrate concentration does not limit denitrification at concentrations greater than 20 mg/L (Paul and Clark, 1989). Denitrification rate increases with increasing NO_3 supply to a maximum and then declines with further increase in NO_3. The decline may be due to high NO_3 content inhibiting the enzymatic reduction of NO to N_2O (Sigunga et al., 2002). Nitrate is the preferred N-form by most vegetables and the optimum NO_3-N : NH_4-N ratio is 3:1 (Barker and Mills, 1980). Hence, the presence of NO_3 in a field (from the application of NO_3-containing fertilizer or from the conversion of NH_4 to NO_3 by nitrification) may stimulate denitrification in situations where N supply was the factor limiting denitrification**.**

In soils, denitrifying activity is highly correlated with water-extractable organic carbon and is frequently stimulated by the addition of exogenous carbon (Knowles, 1982; Hahndel and Isermann, 1993). Different organic compounds which support equal rates of denitrification may give different fractions of N_2O in the products, suggesting that they may exert different effects on the enzymes involved (Knowles, 1982; Reddy et al., 1982). Denitrification studies in columns on soils from south Florida have found that when soil organic matter content is less than 0.91%, it becomes the limiting factor for denitrification, when NO_3 supply is not limiting (Tsai, 1989). In South Florida, soil organic matter content may range from 1% to 2% in sandy soils to 40% to 60% in organic muck soils. Hence, soil organic matter content is not likely to limit carbon availability for the growth of denitrifying bacteria in sandy soils. (Moreover, the confining layer beneath South Florida Spodosols is highly organic). The incorporation of crop residues from vegetables or cover crops, or the application of manure or compost amendments increased soil organic matter content (Clark et al., 1995; Mahmood et al., 1997, 1998; Ozores-Hampton et al., 1994). However, increasing C:N ratio of the organic matter source tends to reduce the denitrification rate. In incubation studies, denitrification rate was highest with vetch (*Vicia illosa* Roth.) residues (C:N of 8 than with soybean (*Glycine max* [L.] Merr) (C:N of 43 corn (*Zea mays* L.) (C:N of 39 and wheat (*Triticum aestivum* L.) residues C:N of 82 (Aulakh et al., 1991b). Information on the effect of crop residue from cover crops used in South Florida such as sorghum Soudangrass (*Sorghum bicolor* (L.) Moench) or sunhemp (*Crotalaria ochroleuca*) on denitrification rates is currently limited.

Denitrification cannot occur under aerobic conditions. Concentrations of dissolved oxygen above 0.2 mg/L suppressed denitrification (Pesek et al., 1971). Under constant soil water content, denitrification rate increases with decreasing oxygen concentration. Under constant oxygen concentration, denitrification rate increases with water content because bacteria have to use oxygen in NO_3 instead of soluble O_2 (Knowles, 1982). In soils, the presence of oxygen and moisture content are linked because soil pores are either filled with water (anaerobic pore) or air (aerobic pores). Hence, soil texture and soil compaction affect denitrification by influencing the tortuosity of soil pore space, hence, the diffusion of substrates to, and products from, the microsites where denitrification occurs. An increase of the water-filled pore space causes a decrease of the oxygen concentration level in the soil, which favors anoxic conditions and hence, an increase in denitrification rate. Denitrification was reported to occur at low levels when soil moisture content was below 60% (Nishio et al., 1988) and was reduced when soil moisture content was below 90% (Craswell and Martin, 1974). In the absence of rain, the seepage-irrigated soils of south Florida can be characterized by decreasing water content from the impermeable spodic layer (the spodic layer is an organic/iron/alumina complex) to the surface of the soil. Hence, the soil just above the impermeable layer is constantly saturated and anaerobic, which favors denitrification. Alternating or contiguous aerobic and anaerobic conditions stimulate concurrent nitrification and denitrification, which may result in greater total N loss from the soil than would be found under continuous anaerobic conditions (Aulakh et al., 1991b).

pH affects denitrification rate and the type of N form released. Denitrification rate was very low at pH=4.1, increased with increasing pH, and was very rapid in the pH range of 7.5 to 8.2 (Pesek et al., 1971; Müller et al., 1980). As pH decreases below 7, nitric (NO) and nitrous oxides (N_2O) become the dominant by-product, while N_2O and N_2 are the dominant by-products at pH above 7 (Bryan, 1981). Hence, liming of agricultural soils or using alkaline irrigation water favors the activity of denitrifying bacteria.

Temperature influences the activity of bacteria and the solubility of oxygen in water and therefore affects denitrification. Temperature also affects the end product of denitrification (Aulakh and Rennie, 1984). When temperature increases, the solubility of oxygen decreases, which favors denitrification. Denitrification rate is negligible at 38 to 45°F, increases with increasing temperature to a highest rate occurring between 145 to 175°F, and ceases at temperatures above 195°F (Knowles, 1982). Denitrification rates measured on columns of an EauGallie fine sand were 5.65, 28.68, and 51.44 ng N_2O-N/g soil/hour at 25, 35, and 45C, respectively (Espinoza, 1997). In south Florida, soil temperature at the 4-inch depth typically ranges between 60 and 80°F during the cropping season (http://fawn.ifas.ufl.edu). Mulching with black plastic polyethylene film increases soil temperature in early spring and late fall to near the optimum range for microbial activity (Thiagalingam and Kanchiro, 1973; Kowalenko and Cameroun, 1976; Shinde et al., 2001). With the exception of potato and green bean, vegetable crops are typically grown with polyethylene mulch in South Florida (Olson, 2004). Hence, denitrification rates in unmulched green bean or potato fields may be lower than those in adjacent mulched fields.

Soil fumigants are often used in vegetable production to reduce soilborne pathogens. Broad-spectrum fumigants such as methyl bromide or chloropicrin also reduce all the levels of denitrifying bacteria. During the three weeks following fumigation, denitrification may occur at reduced rates, or may not occur at all. During most of the growing season, the condition in South Florida's irrigated soils are overall conducive to denitrification:

- N and nitrate levels are high;
- organic matter is incorporated in the tillage zone thereby supplying a carbon source;
- the water gradient above the impermeable layer creates aerobic and anaerobic conditions in proximity to one another;
- soil pH is between 6 and 7;
- and soil temperature is between 60 and 80°F during most of the year.

While all these factors contribute to denitrification, spatial and temporal variability of these factors affect the actual denitrification rate. Moreover, the actual denitrification rate cannot exceed the rate allowed by the most limiting factor. Therefore, actual denitrification rates and potential denitrification rates may be different in the field.

Methods for Measuring Denitrification Rate

The Association of Official Analytical Chemists (AOAC International) has yet to approve a method to measure denitrification in soils. Current methods used to quantify denitrification come from different scientific domains, such as ecology, agriculture, and industrial engineering, and reflect different interests in different aspects of denitrification. Studies comparing different methods to determine denitrification reported different denitrification rates based on methodology used (Aulakh et al., 1991a; Keeney, 1986; Mahmoud et al., 1999). Hence, the appropriate method should be identified and selected before measurements begin. Methods used to measure denitrification may be grouped in two types: the indirect methods and the direct methods. The three most commonly used indirect methods are based on nitrate disappearance, nitrate/chloride ratios, and N balances (Table 1). The direct methods used to determine denitrification activity in fields include isotopic methods (Sidle and Goodrich, 2002), acetylene inhibition (Knowles, 1990), gaseous diffusion (Hauck and Weaver, 1986), prediction models that use micrometeorological data (Hauck and Weaver, 1986) or simple field measurements (Rodriguez and Giambiagi, 1995), and computer simulation (Lin et al., 2000; FAO, 2001). Among these direct methods, the acetylene inhibition technique (AIT) is the most widely used with agricultural soils and can be used in the laboratory as well as in the field (Aulakh et al., 1991a).

The enzyme nitrous oxide reductase normally catalyzes the conversion of N_2O into N_2. When its activity is inhibited by acetylene (C_2H_2), N_2O accumulates. As N_2O concentration in the air is much lower than that of N_2, it can then be quantified by gas chromatography with negligible background interferences (Knowles, 1990). The protocol for the AIT includes:

1. fabrication of a denitrification potential solution (containing sodium succinate and potassium nitrate),
2. mixing the soil sample with the denitrification potential solution in an air-tight capped Erlenmeyer flask,
3. adding ethylene into the flask,
4. calculating the volume of the headspace in the flask,
5. keeping the flask continuously agitated to prevent effects of diffusion,
6. taking air space samples with a syringe, and
7. injecting the head-space sample in a gas chromatograph (Knowles, 1990).

The advantages of the AIT include increase in sensitivity compared to other methods, use of natural nitrate substrate pool, possibility to automate and analyze large number of samples, and relatively low cost compared to the other methods. While simple and versatile, the AIT has some limits:

- acetylene is a poor nitrous-oxide reductase inhibitor at low nitrate concentrations;
- acetylene may inhibit nitrification;
- acetylene may be metabolized by soil microorganisms;
- and contaminants may be present in the acetylene (Keeney, 1986; Knowles, 1990).

Therefore, the AIT method is better suited for short-term measurements of denitrification.

Direct and indirect methods may be used to measure denitrification in the field or in the laboratory. However, it is accepted that three conditions should be met to make valid estimates of field denitrification rates from laboratory measurements. First, the internal environment of the experimental apparatus should be subjected for the duration of the experiment to the same episodic or seasonally cyclical changes that occur in the external environment of the field site. Also, the soil substrate being studied should have inherent heterogeneity and natural properties similar to those of the soil at the field site. Finally, the monitoring and measuring devices and sampling methods should not produce artifacts or create artificial conditions that may alter soil processes.

Progress in understanding and quantifying denitrification has been limited by the lack of uniformity in approaches and standardization in units used to report denitrification rate. Units commonly used to report denitrification rates range from µg of N/cm^3/day to kg of N/ha/year. As an attempt to standardize the description of experimental parameters, Singunga (2003) proposed that temperature (values and fluctuations) and pH be provided. The estimation of potential denitrification should be made under saturated conditions (140% moisture level), in the presence of excess NO_3 and C, and on undisturbed soil cores. The reporting unit should be g N denitrified per kg of soil per hour. Soil mass should be reported on an oven-dry basis.

Compilation of Available Estimates of Denitrification Rates

Denitrification estimates found in the literature from short-term studies (few days) from world-wide ecosystems are overall in good agreement (Table 2). Short-term studies reported denitrification rate in soils from unfertilized areas of 0.57 mg N/g soil/day in a hardwood forest (Brettar and Hofle, 2002) and 0.01 to 0.02 kg N/ha/day for uncultivated land (Ryden, 1985). Other short-term studies reported denitrification rates in highly fertilized agricultural fields (with fertilization rates of 200 to 600 kg N/ha/year) ranging from 0 to 3 kg N/ha/day (Ryden and Rolston, 1983). However, no consensus may be found in published denitrification estimates when all estimates are converted to the same unit and on a yearly basis. By compiling and transforming 94 denitrification rates found in the literature, the average denitrifcation rate (followed by its standard error) was 192±305 kg N/ha/year. These results show that reliable daily estimates of denitrification are available, but their occurrence on a year-round basis is poorly represented by the extrapolation of short-term estimates. There is no guarantee that a denitrification rate measured over a short period will be sustained over a long period of time.

Few denitrification estimates are available from vegetable fields in Florida. Approximately 23% of the N fertilizer was unaccounted for in an N balance made on bell pepper grown in lysimeters (Stanley and Clark, 1993). The N not accounted for was assumed to be lost by denitrification. As the fertilizer rate used in this experiment was 300 lbs N/acre, the potential denitrification estimate from this study was 69 lbs N/acre/season. In another study, denitrification rate was measured every two weeks on undisturbed soil cores from an EauGallie fine sand with the acetylene inhibition technique (Espinoza, 1997). Soil cores were collected from a field where two tomato crops (spring crop between February and June; fall crop between August and December) were grown with seepage irrigation and fertilized each with an N rate of 200 lbs/acre. Actual denitrification rates ranged between 1.4 to 1.9 g N/ha/hr. Actual denitrification measurements were consistently higher than the ones predicted by the LEACHN model (Espinosa, 1997). However, these two denitrification estimates are of limited practical use to help predict the importance of denitrification in designing fertilizer programs for vegetables. The denitrification estimate from lysimeter-grown bell pepper was obtained by difference (Stanley and Clark, 1993) and is likely to over-represent denitrification rate in the field due to the accumulation of error in the fraction determined by difference. The depth of soil sampling in the tomato field was 0-20 cm (Espinoza, 1997). A shallow sampling depth was used in this study to assess the effect of sludge amendment incorporated in the top 20 cm of soil on denitrification. Air content, and thereby oxygen availability in surface soil is much greater than that of the deeper soil layers. Hence, the denitrification estimate from the tomato field (Espinoza, 1997) was largely underestimated.

These results have some implications on fertilizer recommendation and nutrient management. First, denitrification estimates currently available in the literature were made in studies in which the focus was not fertilization management. Hence, it is unlikely that any of them truly represent field-scale denitrification rates for a whole growing season. Therefore, there is no basis for systematically increasing fertilizer applications by amounts that poorly represent denitrification. The second consequence is that fertilizer recommendations need to be based on fertility trials conducted under conditions similar to those of production. Even if denitrification rate is not determined, it is at least factored into the recommendation. Hence, fertilizer recommendations may be higher in denitrification-prone areas (where seepage irrigation is used) than in other areas (deep sandy soils) for similar varieties, production seasons, and yield goals. In addition, improved N management may be achieved though regular monitoring of crop nutritional status by using whole-leaf analysis or fresh petiole-sap testing. With the difficulties associated with long-term field measurement of denitrification, denitrification may be indirectly determined through complete N balances that would include measurement of the different N fractions (crop removal, immobilization and mineralization to and from organic matter, and leaching). Another implication of denitrification on fertilizer management is temporary flooding during the off season. Summer rains often result in the complete flooding of the vegetable fields. Although specific data are not available, it is likely that residual N may be denitrified at that time. As it reduces the potential for N loss to the ground and surface water, maintaining conditions favorable for denitrification during non-cropped periods could become a possible BMP on flatwood soils.

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Table 1. Indirect methods for measuring denitrification in soils.

Method (Reference)	Principle and approach	Advantages	Limitations	Comments
Nitrate disappearance (Hauck and Weaver, 1986)	To follow the disappearance of NO_3 in the sample. The most reliable technique is to use ^{15}N-labeled NO_3 to determine the quantity of NO_3 immobilized or reduced to NH_4. Determining the ^{15}N concentration of the residual NO_3^- allows the measurement of the amount of newly formed NO_3^- by ammonification or nitrification.	Simple method	Considerable sampling error can result from spatial variability of NO_3^- and NO_3^- movement away from the area being sampled.	Accuracy may be increased in the laboratory by measuring the disappearance of nitrate and nitrite, the two ions potentially denitrifiable (Brettar and Höfle, 2002).
Nitrate/chloride ratio (Pratt et al., 1978)	To use the change in NO_3 / Cl ratio as an indirect measurement of denitrification, the amount of N presumably lost is calculated from the change over time in soil solution concentrations of the two ions, correcting for the amount of Cl added directly in rainfall and irrigation water, or though weathering, and for the amount that was removed through crop uptake.	Simple method	It is assumed that Cl moves with NO_3 in soil and that changes in Cl concentrations are known. Large sampling error may result from spatial variability and movement away from the area being sampled.	This method may be used in soil columns leached with a solution of known NO_3 and Cl concentration.
N balance (Hauck and Weaver, 1986)	It is the most common indirect field measurement of denitrification. It involves measuring the difference in N content of a soil plant system at the beginning and the end of an experimental period. The difference is assumed to be due to N loss by denitrification (correcting for N removal via other pathways and for sampling and analytical errors).	Practical method. The net result of opposing N transformations is measured without requiring extrapolations over time and space.	All components of the N balance account cannot be measured with comparable accuracy. The net value for N loss also includes an accumulation of errors due to the interdependence of different N pools.	Despite numerous limitations, the 15N balance method seems to be the most reliable way to estimate overall, long-term (several months to few years) losses from a crop production system. Yet, the cumulative error of the N component estimated by difference may be too big to meaningfully estimate denitrification component.

Table 2. Some published denitrification rates in cultivated fields.

Crop	Soil type	Location	Dentrification			Reference
			Method of measurement	Estimate	Unit	
Asparagus	Sand	South-west Germany	DN potential[z]	1,045	kg NO_3-N/ha/year	Hahndel and Iserman, 1993
Cabbage, salad, celery, beans	Sandy loam	South-west Germany	DN potential[z]	832	kg NO_3-N/ha/year	Hahndel and Iserman, 1993
Cauliflower	Sandy loam	South-west Germany	DN potential[z]	1,256	kg NO_3-N/ha/year	Hahndel and Iserman, 1993
Cereal, potato, lettuce, cabbage	Sandy loam	South-west Germany	DN potential[z]	1,756	kg NO_3-N/ha/year	Hahndel and Iserman, 1993
Cereal, cabbage, lettuce	Sandy loam	South-west Germany	DN potential[z]	1,758	kg NO_3-N/ha/year	Hahndel and Iserman, 1993
Lettuce	Fine loamy	Monterey Co., CA	EPIC model[u]	2.5	g N/m^2 for 6 months[t]	Jackson et al., 1994
Pasture	Sandy	Okeechobee Co., FL	Nitrate disapperance	3.3[w]	µg N/g/day	Tsai, 1989
Pepper	Fine sand	Florida	N balance	69[s]	lbs/a/yr	Stanley and Clark, 1993
Rice, wetland	Clay	South Asia	^{15}N data	2 to 32[y]	kg NO_3-N/ha/year	De Datta, 1995
Rice, wetland	Clay	South Asia	^{15}N balance	146 to 820[x]	kg NO_3-N/ha/year	De Datta, 1995
Tomato	Fine sand	Florida	Acetlyene inhibition	1.4 to 1.9	g N/ha/hr	Espinoza, 1997
Vegetables	Loam	California	Acetylene inhibition	0.1 to 2.88[v]	kg N/ha/day	Ryden and Rolston, 1983
Not specified	Sandy	St. Johns Co., FL	Nitrate disapperance	2.2 to 10.5[w]	µg N/g/day	Tsai, 1989

Table 2. Some published denitrification rates in cultivated fields.

Crop	Soil type	Location	Dentrification			Reference
			Method of measurement	Estimate	Unit	
Not specified	Coarse loamy	Alachua Co., FL	Nitrate disappearance	2.7[w]	µg N/g/day	Tsai, 1989

[z] assuming 1 kg dissolved organic carbon corresponds to a denitrification potential of 1 kg NO_3-N /ha /year
[y] original denitrification rate reported as 0.1% to 2.2% of applied N
[x] original denitrification rate reported as 10% to 56% of applied N
[w] using 3,000 ton of soil/ha (2,000,000 lbs soil/acre), 1 µg N/g/day = 1 kg/ha/year = 1lb/acre/year
[v] 1 kg/ha/day = 400 lbs/acre/year
[u] Erosion/Productivity Impact Calculator
[t] corresponds to 139 g /ha/day for 6 months
[s] original unit was 23% of N applied at a rate of 300 lbs/acre