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Denitrification in agricultural soils: summarizing published data and estimating global annual rates

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Abstract

Information taken from 336 measurements of denitrification in agricultural soils was summarized to assess the influence on denitrification of several factors related to soil, climate, agricultural management and the measurement techniques. The data set is summarized by calculating means and medians and balanced median values (with correction for unbalanced features) for all factor classes in the data set, and by developing a summary model to calculate global denitrification rates for a 0.5 by 0.5 degree resolution. Our results suggest that agricultural fields with high nitrogen application rates and poor soil drainage show higher denitrification values than those with lower nitrogen application rate and good soil drainage. The data also indicate that conditions in wetland rice systems are more prone to denitrification than those in upland cropping and grassland systems. Large uncertainties in the results are caused by differences between the measurement techniques and lack of long-term measurements covering the range of environmental and management conditions found in global agricultural fields.

Introduction

Human activities have accelerated the earth's nitrogen (N) cycle by increasing the rate of nitrogen (N) fixation in fertilizer production, production of N fixing leguminous crops (pulses, soybeans), and fossil fuel combustion (Galloway et al. 1995). N fixation is the transformation of the highly abundant but biologically unavailable atmospheric dinitrogen (N_2) to "reactive" oxidized and reduced N forms such as nitrate (NO_3^-), ammonia (NH_3), nitrous oxide (N_2O) and nitric oxide (NO). Increasing amounts of reactive nitrogen are cycled through soil, ground and surface water, marine systems and the atmosphere which is a cause of concern (Galloway et al. 1995).

In soils and aquatic systems, denitrification removes fixed N that would otherwise be available for primary production. Denitrification is the microbial decomposition of organic matter in which NO_3^- or NO_2^- is the electron acceptor. Denitrification is a facultative anaerobic process and N_2 is the end product. Non-biological denitrification (chemodenitrification) can occur under certain conditions. The main chemodenitrification process is the acid-catalyzed destruction of NO_2^- (Tiedje 1988).

The focus of this paper is on denitrification in agricultural soils, which is an important process for several reasons: (i) N is one of the major factors limiting crop production and denitrification is a very important loss process for N in many agricultural systems (Tiedje 1988); (ii) N_2O, one of the major greenhouse gases, is a by-product of denitrification; and, (iii) Denitrification completes the N cycle and roughly balances the total biological N fixation in the global N cycle (Tiedje 1988).

In agricultural soils NO_3^- originates from fertilizers or is produced by chemoautotrophic nitrifying bacteria that oxidize ammonium (NH_4^+) under aerobic conditions. The sequence of intermediate products of denitrification is as follows (Betlach and Tiedje 1981):

$$NO_3^- \xrightarrow{1} NO_2^- \xrightarrow{2} NO \xrightarrow{3} N_2O \xrightarrow{4} N_2 \quad (1)$$

Factors that influence denitrification rates and the relative production of N_2, N_2O and NO are oxygen concentration, the availability of N and carbon (C), factors related to soil conditions, and climate and management-related factors. Since denitrification is an anaerobic process, oxygen is the most important regulator (Tiedje 1988). Rainfall events, soil texture, soil drainage and tillage influence the amount of oxygen in the soil. NO_3^- is the source of N for denitrifying bacteria and C serves as the electron donor. Increases in both compounds will increase denitrification.

Soil pH has a marked effect on denitrification, with lower rates under acid than under slightly alkaline conditions (Yamulki et al. 1997; Simek et al. 2000). Temperature can influence denitrification both positively and negatively. Denitrification has an optimum temperature, above and below which rates decrease (Beauchamp et al. 1989). Temperature also controls decomposition and nitrification rates (Tiedje 1988), and therefore regulates the availability of oxygen, NO_3^- and C. The NH_4^+ availability for nitrification is influenced by the soil cation exchange capacity (CEC).

Denitrification is strongly variable, both in space and time. This is because "hot spots" of microbial activity occurring as a result of heterogeneity of soil conditions determine the local oxygen status and denitrification (Dowdell and Smith 1974; Duxbury et al. 1982; Myrold and Tiedje 1985; Parkin 1987; Schmidt et al. 1988).

Crop type and fertilizer and animal manure management influence the availability of N. The fertilizer type, N application rate, method and timing of application influence the period of availability of N and the form and way in which N becomes available. Different crops take up N in different patterns and amounts. Finally, the N input from crop residues varies between different crop types and as a result of residue management (e.g., incorporation, burning) (Bouwman et al. 2002a).

The majority of denitrification measurements is based on chamber, soil core and N-balance techniques. Chamber measurements involve the use of enclosures placed over the soil surface in field studies. Two types generally used are enclosures with forced flow-through (often referred to as open chambers), and those with closed-loop air circulation (closed chambers). In the soil core technique intact soil core samples are taken to the laboratory where denitrification rates are measured in sealed incubation jars.

These methods are used in combination with acetylene (C_2H_2) which inhibits nitrification and N_2O-reductase (the last step of reaction 1) (Robertson and Tiedje 1987; Klemedtsson et al. 1988; Klemedtsson and Mosier 1994). The N_2O production is assumed to be equal to denitrification, and denitrification is assumed not to be affected by C_2H_2. Since nitrification is also inhibited, the C_2H_2 inhibition technique can be used only when NO_3^- is non-limiting or when denitrification is not limited by NO_3^- formation by nitrification (Klemedtsson and Mosier 1994). The N_2O concentration measurements in chambers are generally made with gas chromatograph-electron capture detectors.

In the N-balance approach the N inputs and outputs for a given area can be measured, and generally, denitrification is the unaccounted for complement of the balance. ^{15}N is often used as a tracer in N-balance studies. The N balance method generally represents a prolonged period (for example, a complete growing season). The uncertainty in the determination of each of the terms in the N balance is high and the overall result of the balance is sensitive to minor variation in inputs or outputs. In addition, not always all sources and sinks are taken into account in the literature reports used. For example, leaching of NO_3^- is often neglected (Fillery and Vlek 1982; Obcemea et al. 1988; Bacon and Freney 1989; Freney et al. 1990b) and this may cause overestimation of denitrification.

The measurement technique can influence the denitrification process and gas exchange, for example when soil environment and gas diffusion and exchange with the air is disturbed. For example, a problem of the soil core technique is that N_2O may be entrapped in soil and not measured (Mahmood et al. 1999). A further problem of the soil core techniques is the difference in the depth represented by the measurements in the various studies.

The period covered by the measurements determines the amount of fertilizer N recovered as N_2O (Bouwman 1996; Bouwman et al. 2002a) and may thus also determine total denitrification. Moreover, sampling frequencies influence N_2O fluxes measured with chamber methods (Brumme and Beese 1992; Crill et al. 2000), and may thus also be important in denitrification studies with chamber or soil core methods.

There are different types of models describing denitrification in soils. For example, Van Drecht et al. (2003) developed a conceptual model to calculate NO_3^- leaching and denitrification as a fraction of the surface balance N surplus depending on climate, soil texture, soil drainage and soil organic C. A different class of models describes the process of denitrification, for example the DNDC model (Li et al. 1992).

The objective of this study is to summarize data on denitrification measurements. The results may be used to test the above conceptual model of Van Drecht et al. (2003) or process-based models. We use a data set with denitrification measurements from peer-reviewed literature. This data set is unbalanced since it is collected from many research papers with different approaches and methods. Information on soil properties, climate and soil, crop and water management is often not complete. The method used to analyze the data is the residual maximum likelihood (REML) procedure (Payne et al. 2000) which is particularly appropriate for unbalanced data sets.

Materials and methods

Data set

In this study we use an extended version of the data set presented and analyzed elsewhere (FAO/IFA, 2001; Bouwman et al. 2002a; Bouwman et al. 2002c). This data set has 1892 denitrification, NO and N_2O measurements from different parts of the world compiled from the literature, and contains information on various environmental and management factors and measurement techniques (see Appendix). In this paper we summarize the denitrification measurements.

The data is biased. For example, some climate types and classes of other factors are underrepresented. The data set is also unbalanced, because often the data provided is incomplete. In some cases we could add information from other sources. Mean annual precipitation and temperature, which are often not provided in the denitrification reports, were obtained from New et al. (1999) for the coordinates of the measurement sites. Agricultural regions, where most measurements were made, are generally located in homogeneous areas like floodplains with little relief. Therefore, climate data from this 0.5 by 0.5 degree data set is assumed to be representative for the measurement location.

For some factors that are continuous, values are grouped before means and medians are calculated, whereby the number of measurements in each group is as much as possible equally distributed.

The full data set includes 414 denitrification experiments. Part of these are excluded prior to the analysis. Experiments in natural ecosystems (38) are not relevant for the scope of this paper. In 14 studies, chemicals like nitrification inhibitors were used. Because the use of such additives is very limited on the global scale (Trenkel 1997), these studies are also excluded from our analysis. A further eight studies were excluded because of the small number of experiments (gradient measurement method) or lack of information on inputs from biological N fixation (legumes, grass-clover).

Data summary

The data set is summarized in four ways using Genstat 7.1 (Payne et al. 2000):

(i) *Means and medians*. Mean and median values are calculated for each factor-class to indicate skewness of the data set.

(ii) *Balanced medians and Wald test*. Balanced medians are calculated for the factors and factor classes in the data set with the REML directive of GenStat (Payne et al. 2000). The denitrification rates are first log-transformed to obtain a distribution that is closer to a normal distribution than the untransformed data. The literature reference is included as the random variable, and all the other factors are fixed variables. REML calculates means, assuming equally divided numbers of measurements per group and corrects for unbalanced features in the data (Payne et al. 2000). Hence, REML aims at isolating the effect of one factor and eliminating the effect of all other factors. The significance of a factor is determined with the Wald statistic ($P < 0.01$). Wald tests are for fixed model terms. They can be used to test the significance of the fixed model terms as they are added into the model. Because the values are log-transformed they need to be back-transformed to obtain balanced median values (Bouwman et al. 2002a).

(iii) *Model development*. One by one different factors are combined in a model. The difference in deviances between the full and sub-model (full model excluding one factor) can be used as a likelihood-based test to asses the importance of the fixed terms dropped from the full model. Length of measurement period is included as a continuous factor, because its influence was found to be more important than when split up in classes.

(iv) *Summary model*. Based on the results obtained in the previous steps and other considerations a summary model is developed with the following formulation:

$$D = C \exp(\Sigma E(i)) \quad (2)$$

where D is the denitrification (kg ha^{-1} year^{-1} of N), C is a constant (kg ha^{-1} year^{-1} of N) and E is the effect value for factor class i (no dimension).

Extrapolation

The results of the summary model are used to calculate the denitrification rate for each 0.5 by 0.5 degree grid cell with agricultural land use on the global scale with a geographic information system (Van Heerden and Tiktak 1994). Spatial information on agricultural land use and N inputs from fertilizers and animal manure is taken from Bouwman et al. (2005). For soil data (Batjes 1997) we use the properties of the dominant soil, excluding all soils considered to be unsuitable for agriculture based on a land evaluation procedure. In the soil drainage map (Batjes 1997) the soil drainage classes are regrouped into poor and good drainage to be consistent with the classification of the denitrification data set (Appendix). Because leguminous crops are excluded from the data set, denitrification for these areas is not calculated.

Results and discussion

Data summary

Extreme denitrification levels occur in specific factor classes. For example organic soil material shows high denitrification values, because these soils are generally (partly) anaerobic and the soil organic C content is high. Denitrification measurements in organic soils (18 experiments) strongly influence the median and balanced median denitrification rates for mineral soils due to interaction effects. A similar effect was also found in the analysis of N_2O emissions (Bouwman et al. 2002a). To eliminate this undesirable effect we exclude organic soils from further analysis. Since organic soils are used in only a very minor part ($<7\%$) of the global agricultural area (Bouwman 1990), this will not have a major effect on our extrapolation.

Hence, out of the data set of 414, we exclude experiments in natural ecosystems (38), and experiments with organic soils (18), the crop types legumes (2) and grass-clover (5), chemical additives like nitrification inhibitors (14), and the gradient measurement method (1), and 336 measurements remain for the data summary and the model development.

Soil pH is the only soil property having a significant influence on denitrification based on the Wald test. Both the median and balanced median denitrification rates increase with increasing soil pH (Table 1) and confirm the expectations based on the literature. All other factors related to soil and climate conditions are found not to have a significant influence.

Table 1. Mean, median and balanced median of denitrification and number of experiments (*N*) per factor class[a].

Factor class	*N*	Mean	Median	Balanced median
		kg ha^{-1} of nitrogen		
Soil pH[b]				
0–5.5	42	24	4	3
5.5–7.3	162	17	7	6
7.3–8.5	49	8	5	8
> 8.5	16	13	10	17
Soil drainage[c]				
Poor	113	22	8	9
Good	116	13	6	6
Crop type[b,c]				
Grass	89	17	4	6
Upland crops	138	15	5	3
Wetland rice	68	21	21	8
None	29	51	21	17
Fertilizer type[b,c,d]				
AN	40	17	5	5
CAN	10	20	9	13
KN	30	22	9	7
Mix	7	14	14	7
AS	6	51	18	15
AM	59	22	5	5
U	124	18	12	5
N-rate (kg/ha)[b,c]				
0	49	20	2	4
1–75	56	9	6	5
75–150	112	15	9	6
150–225	50	14	7	7
225–300	22	27	25	13
> 300	46	49	29	15
Method of measurement[c]				
N balance study	104	23	19	24
Closed chamber	65	21	4	7
Soil core method	155	18	6	7
Open chamber	12	10	2	3
Length of measurement period (days)[c]				
0–80	143	19	12	6
80–160	91	10	4	6
160–240	36	34	11	8
> 240	53	32	7	12

[a]Classifications for fertilizer type, N rate and length of measurement period differ from those in the Appendix.
[b]Significant factors on the basis of the Wald test.
[c]Significant factors on the basis of model development.
[d]Grouped because of absence of important differences in the balanced median for the individual fertilizer types; AN = ammonium nitrate, ammonium sulphate, ammonium phosphate, and anhydrous ammonia; CAN = calcium ammonium nitrate, KN = potassium nitrate/sodium nitrate/calcium nitrate, Mix = combination of various synthetic fertilizers, AS = combination of animal manure and synthetic fertilizers, AM = animal manure, U = urea, urine, and urea-ammonium nitrate.

The management-related factors with significant influence on denitrification based on the Wald test are crop type, fertilizer type and N-rate (Table 1). With regard to the crop type, high denitrification rates are seen for bare soil, which may be due to the absence of crop N uptake. The group of upland crops has low median and balanced median denitrification values relative to grass and wetland rice. Grassland may have higher denitrification rates than upland crops under the same conditions. This may be related to biological activity which is often higher in soils under grassland than in arable soils, because of high availability of organic material, deep root systems and longer growing season than most crops.

The data suggest that conditions in wetland rice systems are prone to high denitrification rates. Generally wetland rice fields are inundated or wet conditions are maintained during the rice crop period. In the post-harvest period the area is drained and nitrification and subsequent and denitrification can take place, as indicated by high N_2O fluxes in this period (Bouwman et al. 2002a). Since most measurements cover the growing season only, the annual denitrification may be underestimated. However, it is clear that since NO_3^- leaching from wetland rice systems is generally low as suggested by Zhu and Chen (2002), ammonia volatilization (Bouwman et al. 2002b) and denitrification are the dominant loss pathways for N in wetland rice systems. In fact, there is an interdependence between ammonia volatilization and denitrification, whereby one process may dominate in some years and the other process in other years (Freney et al. 1990a, b; Freney and Denmead 1992), depending on, for example, weather conditions.

A remarkable feature is the difference between the mean, median and balanced median for wetland rice and the fertilizer type U. This may be caused by an interaction of different factors. In the data set urea is mostly used in experiments with wetland rice. The fact that for wetland rice and the fertilizer type U the balanced median is much lower than the median and mean may be caused by the climate correction by REML, which may not be correct. Rice is grown exclusively in mediterranean, tropical and subtropical climates. By assuming that fertilizer type U is used equally for all crops, the REML procedure may yield unrealistic values for these fertilizer types.

The fertilizer types CAN and AS have higher balanced medians than the other fertilizer types (Table 1). For CAN this may be related to the calcium in the fertilizer which may cause a (local) soil pH increase leading to enhanced denitrification (see above). The high denitrification levels of AS can be explained by the addition of C and inorganic N, creating conditions prone to denitrification. However, the balanced medians are uncertain, because in the data set there are only 10 measurements for CAN and 6 for AS.

No factors related to the measurement technique are significant. However, the balanced median for the length of measurement period indicates increasing denitrification with increasing duration of the experiment (Table 1).

During the model development we found that the factors with a significant effect on denitrification are soil drainage, N-rate, fertilizer type, crop type, method of denitrification measurement and length of the measurement period (Table 1). This is different from the factors found to be significant with the Wald test for the balanced medians, where the factors soil drainage, length of measurement period and method of denitrification measurements are not found to have a significant influence, while soil pH is an additional significant factor. This is due to the difference in approaches (see Section 2.2).

The factor length of measurement period also shows a significant effect, whereby experiments covering long periods yield higher denitrification rates than those covering short periods (Table 1). Finally, the factor method of measurement is significant. The N-balance method shows higher denitrification values than all other measurement methods (Table 1). However, on the basis of this study we cannot judge which denitrification measurement method is most reliable.

The factors added to the summary model include soil drainage, N rate, crop type, measurement method and length of measurement period. The factor soil drainage expresses that in poorly drained soils anaerobic conditions are more easily reached and maintained for longer periods, thus leading to higher denitrification rates than in well drained soils. The factor N-rate represents the N availability driving the nitrification and denitrification processes. The effect of crop type in the summary model is similar to that expressed by the balanced medians, with increasing values in the order upland crops – grassland – wetland rice (Table 2). In the summary model the length of measurement period is a constant representing 1 year (Table 2). Mean effect levels of all other factors are also included in the constant (Table 2).

Although fertilizer type has a significant influence on denitrification rates, this factor was deliberately excluded when formulating the summary model, because of the interaction effects noticed above. In addition, the high denitrification rates calculated for CAN and AS are based on

Table 2. Effect values (*E*) of the summary model.[a]

Factor class	Effect value
Soil drainage	
Poor	0
Good	−0.478
N-rate	
0	0
1–75	0.119
75–150	0.524
150–225	0.658
225–300	1.147
> 300	1.338
Crop type	
Grass	0
Upland crops	−0.345
Wetland rice	0.425
None	0.943
Method of measurement	
N balance study	0
Closed chamber	−0.807
Soil core method	−0.920
Open chamber	−2.000

[a] Effect values (*E*) are dimensionless. According to Equation (2) the denitrification $D = C \exp(\Sigma (E(i))$, where $C = 33.6$ kg ha^{-1} year^{-1} . The constant *C* incorporates the effect value for 365 days (1 year) for length of measurement period (2.9), times the mean effect for all factors not included in the summary model (11.7). For the combination poor soil drainage, N-rate = 1–75 kg N ha^{-1}, upland crops, and soil core method, $D = 33.6 \exp(0+0.119-0.345-0.920) = 11$ kg ha^{-1} year^{-1} of N (see Table 4).

only a few experiments, while the other fertilizer types show comparable results (Table 1). Hence, the summary model yields effect values for the mean of all fertilizer types.

Soil organic C content and soil texture were expected to be important on the basis of the literature. However, our results show no significant influence of these factors on denitrification. Regarding soil texture there are different explanations. Firstly, the effect of soil drainage may be stronger than that of soil texture and soil organic C content, because it combines information on texture and other soil properties with the hydrological conditions. Secondly, the classification of soil texture in three classes may be too coarse to separate the soil texture effect. Thirdly, information on soil texture provided in the literature is often vague or incomplete, which makes interpretation difficult.

On the basis of the literature climate is also expected to be an important control, because it governs organic matter decomposition, denitrification and nitrification rates. One hypothesis is that denitrification is faster at high than at low temperatures, but plant biomass production is greater too, leading to more competition between crop N uptake and denitrification. Precipitation is probably not a significant factor because the data set includes many measurements in irrigated or wetland systems where the influence of precipitation is largely eliminated. Furthermore, there may be a bias towards temperate humid climates in the measurements in rainfed systems.

During the analysis a strong effect of the classification of factors was observed. In addition, interrelationships between factors can occur. These interrelationships have not been investigated because of the large number of factor-classes and a lack of knowledge with respect to the mutual connections.

We illustrate the uncertainty in the model results with an example for the combination of factor classes with most measurements and thus least uncertainty. This combination is upland crops, N-rates between 75 and 150 kg ha^{-1}, good soil drainage conditions and the soil core method. On the basis of the standard errors per factor we calculate a range of 2–46 kg ha^{-1} year^{-1} of N around the model estimate of 10 kg ha^{-1} year^{-1} of N.

The lowest value of denitrification (15 kg ha^{-1} year^{-1} of N) for the N-balance method (Table 3) is found in grid cells with good soil drainage, upland crops and N-rate of 0 kg ha^{-1}; the maximum value of denitrification (196 kg ha^{-1} year^{-1} of N) is found in grids with poor soil drainage, wetland rice and N-rate > 300 kg ha^{-1}. For the soil core method the minimum denitrification rate is 6 kg ha^{-1} year^{-1} and the maximum is 78 kg ha^{-1} year^{-1} of N (Table 4). Hence, the difference between the two measurement methods is about a factor of two.

In the data set, the lowest reported denitrification rate is 0 and the maximum value is 341 kg ha^{-1} year^{-1} of N over the measurement period. Hence, the range of values in the data set is larger than that obtained with the model. This is the result of the log-transformation of the denitrification rates which yields a mean whereby the effect of outliers is reduced. Therefore, emissions from measurements reported in individual research papers for specific sites can not be predicted by the model developed in this study. The estimated denitrification for factor class combinations is more relevant for upscaling to 'landscape' conditions.

Uncertainty that can not be deduced for the model is related to the incompleteness of the data. The data set does not reflect all management and environmental conditions found in the agricultural systems of the world. For example, measurements in tropical upland cropping systems are under-represented. Also, the data set is dominated by measurements in industrialized countries with high atmospheric N deposition (Bouwman et al. 2002d). Denitrification in countries with low deposition rates may therefore be overestimated by the model. In addition, N inputs from biological N fixation and crop residues are often not reported but may have contributed to observed denitrification in many experiments.

It should be noted that, when used to predict denitrification, the model development should, in fact, be performed on the basis of the data used in the upscaling. However, this is not possible because the spatial information with 0.5 by 0.5 degree resolution does not depict the conditions at the specific measurement sites described in the literature reports used.

Table 3. Estimates for denitrification in kg ha^{-1} $year^{-1}$ of N for the different combinations of soil drainage, N-rate and crop type for the N-balance method.

Soil drainage/ crop type	N-rate					
	0	1–75	75–150	150–225	225–300	> 300
Poor						
Upland crops	24	27	40	46	75	91
Grass	34	38	57	65	106	128
Wetland rice	51	58	87	99	162	196
Good						
Upland crops	15	17	25	29	46	56
Grass	21	23	35	40	66	79
Wetland rice	32	36	54	62	100	122

Table 4. Estimates for denitrification in kg ha^{-1} $year^{-1}$ of N for the different combinations of soil drainage, N-rate and crop type for the soil core method.

Soil drainage/ crop type	N-rate					
	0	1–75	75–150	150–225	225–300	>300
Poor						
Upland crops	9	11	16	18	30	36
Grass	13	15	23	26	42	51
Wetland rice	20	23	35	40	65	78
Good						
Upland crops	6	7	10	11	19	22
Grass	8	9	14	16	26	32
Wetland rice	13	14	21	25	40	48

Extrapolation

The spatial factors in the summary model are soil drainage, crop type and N-rate. The effect values for soil drainage and N-rate (including synthetic fertilizers, animal manure and combinations) for different crop types (Table 2) are used to compute denitrification with Equation (2) for each 0.5 by 0.5 degree grid cell with agricultural land use.

The factors method of measurement and length of measurement period in the summary model are non-spatial factors. We compare our extrapolation based on the N-balance method with the soil core method to obtain a wide range of denitrification rates. The extrapolations based on open (due to the small number of observations) and closed chamber measurements (because the effect value is close to that of the soil core method) are not presented.

Figure 1 shows high estimates for denitrification rates in different world regions in 1995 based on the summary model. For example, in the east of China, high application rates combined with the inundated conditions in wetland rice fields cause high denitrification losses according to our results. In major parts of North and South America, Africa, Saudi Arabia and Australia, low denitrification values are associated with low N application rates and good soil drainage.

Total annual denitrification calculated for the global agricultural area (excluding leguminous crops) is 87 Tg $year^{-1}$ of N for the N-balance method in the year 1995, and 22 Tg $year^{-1}$ for the soil core method. This is in good agreement with the model of Van Drecht et al. (2003), who estimated a total annual denitrification of 56 Tg N (also leguminous crops excluded).

When considering the results presented in Figure 1 some points must be kept in mind. The grid size of the 0.5 by 0.5 degree grid cells is about 55 by 55 km at the equator. Much of the heterogeneity within each grid cell is not reflected in the data (e.g. soil and management conditions).

Besides that, the N input data are mostly national averages, and do not describe the variation in fertilizer and manure management within countries.

Conclusions

We summarize 336 denitrification measurements that represent a range of different measurement techniques to measure denitrification for different environmental and management conditions. We developed a summary model based on our findings, which describes higher denitrification rates for poorly than for well-drained soils, increasing rates along with increasing N inputs from fertilizers and animal manure, and an increase in the order upland crops – grassland – wetland rice. The N-balance method of denitrification measurement yields highest denitrification rates and open chamber measurements the lowest.

Total denitrification calculated with our summary model for the year 1995 for the global agricultural area (excluding leguminous crops) is 87 Tg year^{-1} of N based on effect values for the N-balance method of denitrification measurement,

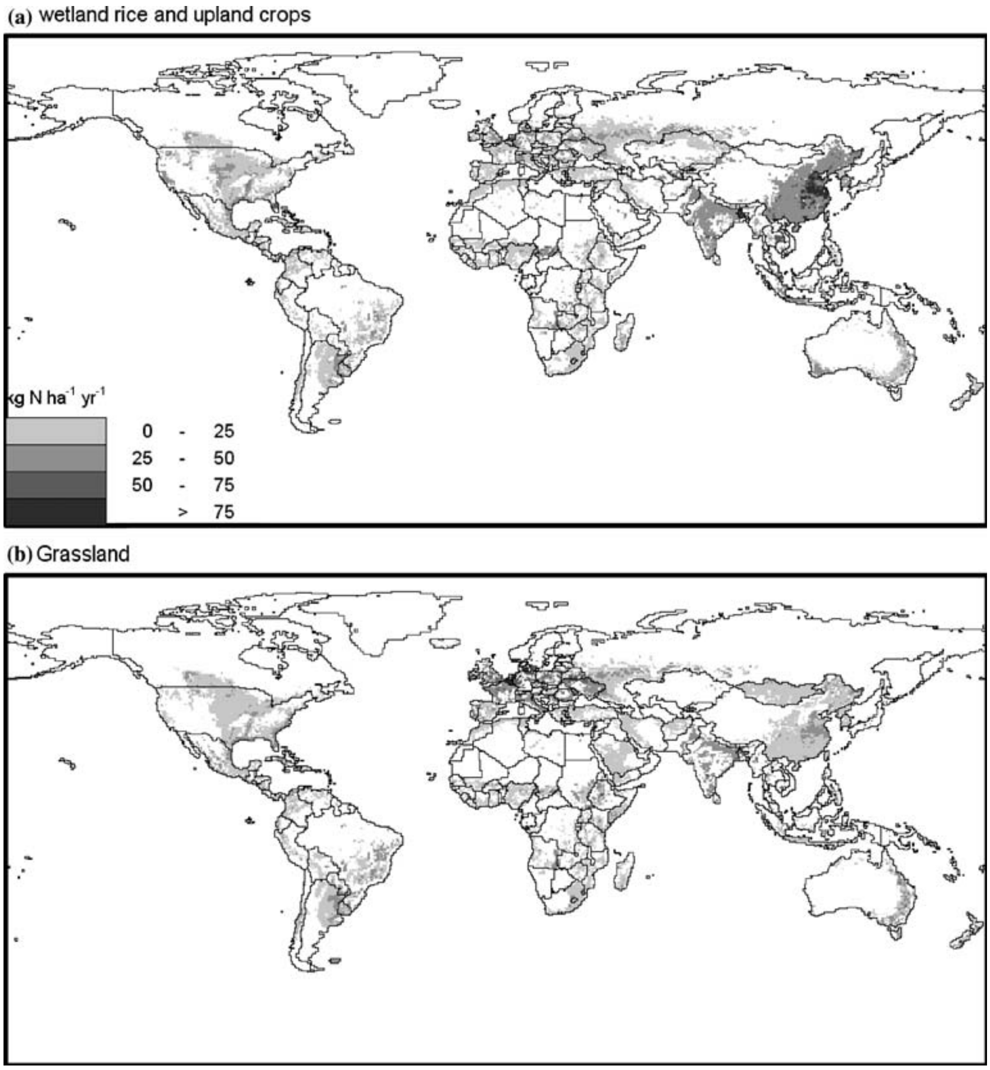

Figure 1. Estimated denitrification rates with the summary model based on the N-balance method for (a) arable land (upland crops and wetland rice) and (b) grassland. Denitrification rates for the soil core method (not presented) are lower than those for the N-balance method.

and 22 Tg year^{-1} of N for the soil core method. This indicates that perhaps the largest uncertainty in the results is caused by the differences between the measurement techniques used. Further uncertainties are caused by various factors. The data set is biased, some groups being underrepresented, and information is not complete for each experiment. The results are sensitive to the classification for factors into classes, a problem that is very difficult to solve. A further uncertainty is caused by lack of data on N inputs from N deposition, crop residues and N fixation, which in many regions may have a considerable contribution to total N inputs.

To improve our knowledge on denitrification at the landscape scale, more measurements are required. These should cover the heterogeneity of global agricultural fields and should be standardized as much as possible and cover a period of at least 1 year. This will result in a more balanced data set.

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Appendix

Table A1. Factors and factor classes in the data set and number of experiments (*N*).

Factor/Factor class	*N*
Soil texture	
Coarse	238
Medium	84
Fine	59
Organic	18
Not reported	15
Soil organic C content (%)	
0–1	29
1–3	174
3–6	70
> 6	34
Not reported	107
Soil N content (%)	
0–0.05	0
0.05–0.15	106
0.15–0.30	93
> 0.30	51
Not reported	164
Soil drainage	
Poor	148
Good	149
Not reported	117
Soil pH	
0–5.5	51
5.5–7.3	212
7.3–8.5	58
> 8.5	16
Not reported	77
CEC (cmol kg^{-1})	
0–24	55
24–32	23
> 32	27
Not reported	309
Bulk density (g cm^{-3})	
0–0.5	12
0.5–1	24
1–1.5	74
> 1.5	8
Not reported	296
Climate type	
Temperate, continental	71
Temperate, oceanic	132
Subtropical, summer rains	88
Subtropical, winter rains	57
Tropics, warm humid	46
Tropics, seas. dry	0
Cool tropics	0
Boreal	2
Arid	0
Polar/alpine	0
Crop type	
Grass	127
Upland crops	138
Wetland rice	68
Bare soil	32
Other	44
Not reported	5
Fertilizer type	
Anhydrous ammonia, ammonium bicarbonate/sulphate/phosphate	9
Ammonium nitrate	38
Calcium ammonium nitrate	16
Potassium nitrate/sodium nitrate/calcium nitrate	38
Mix of fertilizers	8
Combination of manure and synthetic fertilizers	8
Animal manure	61
Urea and urine	131
Urea-ammonium-nitrate	8
Fertilizers with various chemicals	14
Grazing	2
None	78
Not reported	3
N application rate (kg ha^{-1})	
0	78
< 50	10

Table A1. (Contd).

50–100	131
100–150	39
150–200	27
200–250	35
> 250	92
Not reported	1
Application method	
Broadcast	173
Incorporated	80
Solution	42
Incorporated and broadcast	1
Not applicable (for N rate = 0)	78
Not reported	40
Timing of application	
Single	210
Single, but part of split	32
Split	77
Not applicable (for N rate = 0)	78
Not reported	95
Length of measurement period (d)	
0–120	205
120–180	78
180–240	40
240–300	7
> 300	69
Not reported	15
Method of measurement	
N balance	110
Closed chamber	77
Soil core method	200
Open chamber	26
Gradient	1
Not reported	0
Frequency of measurements	
More than one per day	4
Daily	48
One per 2–3 days	49
Once per 3 days to 1 week	143
Less than one per week	170

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