

Regional scale analysis of denitrification in north temperate forest soils

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Abstract

Large scale analyses of biogeochemical processes are necessary for understanding anthropogenic effects on global climate and environmental quality. Regional scale estimates of denitrification from forest soils in southern lower Michigan USA were produced by stratifying the region into landscape experimental units using soil texture and natural drainage classes, and extrapolating data to larger areas using a geographic information system (GIS). Previous landscape-scale research established relationships between soil texture and drainage and denitrification and quantified annual denitrification N loss in nine soil texture/drainage groups. All forest soils within the region (**64** series) were assigned to one of these nine groups based on their texture and drainage characteristics and were assigned an annual denitrification N loss value. A regional estimate of denitrification was produced by multiplying the areal extent of each of the nine soil groups by their annual denitrification N loss value. Loam-textured soils underlie **47%** of the regional forest and accounted for **73%** of the forest denitrification. Sandy soils were found under 44% of the regional forest but produced only **5%** of the regional denitrification. Clay loam soils underlie **9%** of the regional forest and produced **22%** of the denitrification. Annual denitrification N loss for the region was estimated as **1.4×10^7 kg N/yr**. We used denitrification enzyme activity (DEA) as a proxy for annual denitrification N loss to determine if the relationship between denitrification and soil texture and natural drainage that we observed at the landscape scale held up at the regional scale. DEA was measured in **22** soils across the region and was strongly related to soil texture and natural drainage ($r^2 = 0.61$), suggesting that extrapolation of data from the landscape to the regional scale was justified.

Introduction

Interest in large scale estimates of biogeochemical processes has increased greatly in recent years due to concern about anthropogenic effects on global climate and environmental quality (Mooney *et al.*

1987; Schneider **1989**). Study of broad scale biogeochemical processes is hindered by a lack of conceptual and experimental approaches to collection, extrapolation and validation of large scale biological data sets. Current large scale estimates of biogeochemical processes are highly uncertain and

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poorly validated and are therefore insufficient to address questions relating to climate change and environmental quality at regional or global scales (Jeffers 1988; Aselmann 1989).

In this paper, we present data from a regional scale study of denitrification in north temperate forest soils. Denitrification is the production of nitrogen gases (N_2 , N_2O , NO) by soil bacteria that use nitrate (NO_3^-) for respiration in the absence of oxygen. One of the gaseous products of denitrification, N_2O , affects levels of stratospheric ozone and is an important absorber of infrared radiation (Rasmussen and Khalil 1986; Cicerone 1987). Denitrification is also important in depleting soil fertility and reducing NO_3^- pollution of groundwater (Keeney 1987). Denitrification has been studied in bacterial cultures and in field plots for over 100 years (Payne 1981), but few studies have produced large scale estimates of this process. Such estimates are needed to evaluate the role of denitrification in atmospheric chemistry and for calculating large scale N budgets for agricultural, forestry, municipal waste treatment and coastal management practices.

We studied regional scale dynamics of denitrification using an approach based on soil geography. There are systematic relationships between soil properties and many aspects of ecosystem structure and function (Jenny 1980; Pregitzer *et al.* 1983; Pastor *et al.* 1984; Schimele *et al.* 1985; Bouma *et al.* 1986; Swanson *et al.* 1988; Matson *et al.* 1989). Denitrification is influenced by soil texture and natural drainage characteristics that are major components of soil classification system (Groffman and Tiedje 1989a). Soil classification information is available for large areas of the globe and is frequently being combined with land use and other information into digitized geographic information systems (Reybold and TeSelle 1989). These systems have great potential as research tools for study of biogeochemical processes at a regional scale (Burke *et al.* 1989; Burrough 1989).

In this study, we produced regional scale estimates of denitrification in forest soils of the southern portion of the state of Michigan, USA. Our approach was to extrapolate data from a landscape scale denitrification study (Groffman and

Tiedje 1989a, b) to the regional scale using a GIS containing soils and land use information. We also developed a method to determine if our regional scale extrapolations were valid. Our objectives were 1) to analyze regional scale patterns of denitrification activity, 2) to produce large scale estimates of denitrification for regional and global N budgets and 3) to test a methodology for validating extrapolation of denitrification data from experimental sites to larger areas.

Experimental background and approach

In our previous study, we estimated field scale annual fluxes and characterized landscape scale variation of denitrification in forest soils in southern lower Michigan (SLM), USA. Landscape units in this region were defined as a topographic sequence of soils, or a catena. Soils of similar texture arranged in adjacent topographic positions differ in soil wetness, or natural drainage. Three catenas (profile textures of clay loam, loam, sand) that represented the range of soil textures present in the region were chosen within an 80 km² area of SLM. Each catena encompassed three natural drainage classes (well, somewhat poorly, poorly), which together with the three textural types provided a matrix of nine soil groups. Thus, to study the landscape we sampled 'field' units (each natural drainage class within a catena) and to study regional scale dynamics, we sampled a range of landscape units (the catenas of different texture).

Estimates of annual N gas production by denitrification in each of the nine soil groups were produced by intensive field sampling over the course of a year (Table 1). Denitrification was measured at all nine sites, using a soil core technique, 12 times in 1985 (20, 2.0 × 15 cm cores per site per data). Sampling was weekly during the period of highest flux (early spring) and monthly at other times. Methods and results are detailed in Groffman and Tiedje (1989a).

Landscape scale denitrification variability was associated with soil texture and natural drainage. We were able to explain 86% of the variability in annual denitrification N loss with a multiple regres-

sion model using soil texture (percent sand) and an index of natural drainage (Schaetzl 1986) as predictor variables (Groffman and Tiedje 1989b). Poorly drained soils had higher rates of denitrification than well drained soils and fine-textured soils (clay loams and loams) had higher rates of activity than sandy soils.

In the study presented here, we extrapolated data from our landscape study to the regional scale using a GIS containing soil texture and natural drainage and land use information for the SLM region. We were able to conduct a regional scale analysis because the landscape scale study was designed to systematically address the range of landscape types within the region, and the strong statistical relationship between denitrification and soil texture and natural drainage suggested that we had successfully defined landscape scale denitrification controls. Regional scale analysis was needed to define regional scale controls of the process, and to produce estimates of denitrification relevant to atmospheric chemistry and water quality questions.

A major problem in regional scale studies is validating the extrapolation of data from experimental sites to larger areas. Given that there is currently no way to measure soil-atmosphere N_2 fluxes over large areas, we could only test the validity of our spatial extrapolation by determining if the patterns of denitrification with soil texture and natural drainage that we observed at the landscape scale held up over a regional area. To fully carry out this validation, we would have had to measure denitrification over several years in a variety of sites similar to those in our original study. To avoid this costly and time consuming effort, we investigated an alternative way to validate our regional estimates. Previous work showed that the annual mean of denitrification enzyme activity (DEA) was strongly related to annual denitrification N loss (r^2 as high as 0.96) within our original nine soil groups (Groffman and Tiedje 1989b). Previous work also found that the annual mean of DEA is much easier to measure than annual denitrification N loss, since DEA varies much less over the year than actual denitrification rate (a factor of 2 or 3 rather than 1000). We measured DEA at one time during the year in a range of soils wider than those in our origi-

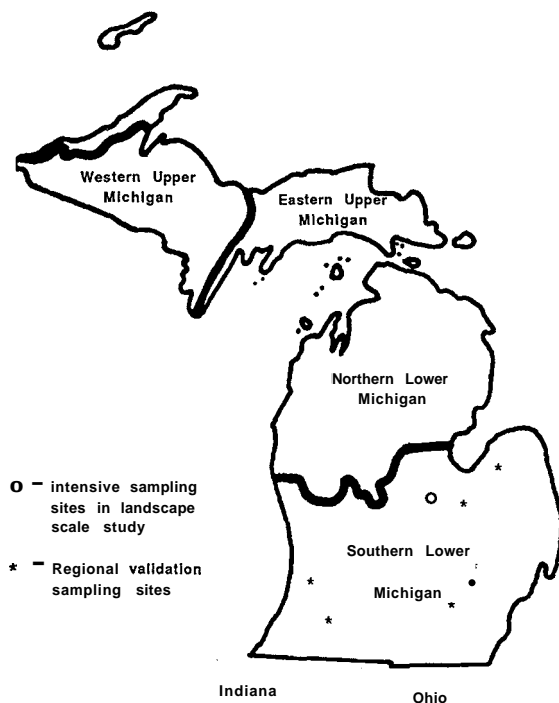


Fig. 1. Classification of regions within the state of Michigan by integration of climate and physiographic factors (Albert *et al.* 1986), and location of study sites in southern lower Michigan. Each point represents the location of a catena consisting of well, somewhat poorly and poorly drained soil series.

nal study, to validate the extrapolation of data from our landscape scale study to the regional scale.

Methods

Study area

The SLM region (Fig. 1) consists of the area from the Indiana/Ohio-Michigan border to approximately the climatic boundary between mesic and frigid soil temperature regimes (Michigan State University 1981; Albert *et al.* 1986), and covers approximately 6.95×10^6 ha. Climate within the region is highly uniform and variation in biological processes is primarily controlled by physiography (Albert *et al.* 1986). The major landforms in the region are lake plain (clay and sand), ground and end moraine, and outwash plain, each of which has

Table 1. Annual N loss (kg N ha⁻¹ y⁻¹) to denitrification in nine forest soil groups in lower Michigan, 1985. Adapted from Groffman and Tiedje (1989a).

Natural drainage class	Profile texture		
	Clay loam	Loam	Sand
Well drained	18	10	0.6
Somewhat poorly drained	17	11	0.8
Poorly drained	40	24	0.5

distinctive patterns of soils and vegetation. Clay loam soils are associated with the clay lake plain, loams are associated with the moraines, and sandy soils are associated with the outwash and sandy lake plains. Maple-beech forests are the dominant natural vegetation on the fine-textured soils while oak is more common on the sandy soils (Albert *et al.* 1986). Although clay lake plain dominates the eastern third of the region, moraine the center third, and sandy lake plain and outwash the western third, there is considerable heterogeneity of landforms (and thus soils) throughout the region.

Extrapolation techniques

Our previous study quantified annual denitrification N loss in soils representative of nine soil texture/drainage groups (Table 1). To produce a regional scale estimate of denitrification, all soils within the region were placed in one of these nine groups, and the areal extent of each of the soil groups under forest cover was determined and multiplied by an annual denitrification N loss value from Table 1. Soil and land use data was derived from a GIS containing soil association and land use information in 333 m² pixels. Soil association information was digitized from a soil association map of Michigan (Michigan State University 1981; Lusch and Enslin 1984). A soil association is a landscape unit that has a distinctive proportional pattern of soils. Associations often consist of soils that are closely related and are frequently similar in size and composition to the catena units used in our landscape scale study. Association units were broken into component soil series by assuming percent distributions of individual series within associations

(Vitosh and Mokma 1983). For a two soil association, we assumed that 60% of the area consisted of the first series and 40% consisted of the second. For a three series association, the breakdown was 45-35-20 and for a four series association the breakdown was 40-30-20-10. Using these assumptions, each pixel of our study area was broken into component soil series and each series was assigned one of the nine annual denitrification N loss values from Table 1. Southern lower Michigan is mapped with 41 different soil associations comprising 64 individual soil series.

Land use information was digitized from a land cover map of Michigan derived from visual interpretation of multiple Landsat thematic mapper and multi-spectral scanner scenes (Lusch and Enslin 1984). Level I classification of urban, agricultural, aquatic and barren land uses and level II classification of forest (deciduous versus coniferous) and wetland (forested versus non-forested) land covers are depicted on this map. Classifications were validated by comparison of selected pixels with other land use/land cover data bases. Since our denitrification data base came only from forest soils, only pixels identified as 'deciduous forest' or 'forested wetlands' were included in the regional scale analysis.

Validation sampling

We used DEA as a proxy for actual annual denitrification N loss to validate the extrapolation of data from our experimental sites to the entire region. Given the difficulty of measuring soil-atmosphere N gas fluxes over large areas, the only type of validation we could attempt was to determine if the patterns of denitrification with texture and drainage that we observed at the landscape scale held up at the regional scale. In the landscape-scale study, actual annual denitrification N loss (kg N ha⁻¹ y⁻¹) was associated with percent sand (SAND) and drainage index (DI) by:

$$\text{Denitrification} = 0.34 (\text{DI}) - 0.40 (\text{SAND}) \quad (1) \\ + 11.81, r^2 = 0.86, \\ p < 0.003, n = 9$$

Table 2. Land use and denitrification ($\text{kg} \times 10^6 \text{ N ha}^{-1} \text{ y}^{-1}$) for different textures of soils in southern lower Michigan (south of approximately 44°N latitude). Total land area = 6.95×10^6 ha, total forest area = 1.71×10^6 ha.

Profile texture	Percent of region	Percent in agriculture	Percent in forest	Percent of regional forest	Annual denitrification	Percent of regional denitrification
Clay						
loams	15	74	13	9	3.0	22
Loams	63	73	18	41	10.2	73
Sands	22	41	48	44	0.7	5
Total					13.9	

In the landscape-scale study, DEA ($\text{ng N g}^{-1} \text{ h}^{-1}$) was associated with actual denitrification N loss by:

$$\text{Denitrification} = 0.09 (\text{DEA}) + 0.92, \quad (2)$$

$$r^2 = 0.73, p < 0.003,$$

$$n = 9$$

In the landscape scale study, DEA was associated with soil texture and drainage by:

$$\text{DEA} = 2.83 (\text{DI}) - 3.39 (\text{SAND}) \quad (3)$$

$$+ 134.30, r^2 = 0.66, p < 0.04,$$

$$n = 9$$

For our validation studies, we used equation 3 to predict DEA at 22 locations across a wide area of SLM (Fig. 1). Catenas of different textures were chosen to replicate our original design, selecting soil series identical or similar to those in our original study. The 22 sites selected were chosen to produce four loam, two sand and two clay loam catenas consisting of well, somewhat poorly and poorly drained soils. One sand and one clay loam catena lacked somewhat poorly drained soils. All sites were sampled over a two day period in June 1986 and DEA was measured using the short term anaerobic assay described by Smith and Tiedje (1979). This assay measures the quantity of denitrification enzymes present in soil at the time of sampling. Percentage sand was determined by particle size analysis (Day 1965), and drainage index was calculated using the formulas given by Schaetzl (1986).

Results

Interactions between land use and soil patterns affected forest denitrification in SLM (Table 2).

Loam and clay loam soils are more extensively cropped than sandy soils and as a result, sandy soils underlie almost 50% of the regional forest, despite covering only 22% of the land area. Loams account for 47% of the regional forest despite covering 64% of the regional area and clay loams occur under 9% of the regional forest and 15% of the regional area. Eventhough the sandy soils represented a significant portion of the regional forest, their low activity greatly reduced their contribution to regional forest denitrification (5% of regional activity). Conversely, loam and clay soils contributed almost twice as much denitrification as the proportion of regional forest area that they represented (Table 2).

DEA was related to soil texture (expressed as percentage sand) and natural soil drainage (as represented by drainage index) in the 22 soils sampled across the region:

$$\text{DEA} = 7.82 (\text{DI}) - 3.62 (\text{SAND}) \quad (4)$$

$$- 16.80, r^2 = 0.61, p < 0.005,$$

$$n = 20$$

Actual and predicted DEA were highly correlated ($r^2 = 0.56$), but measured DEA was generally higher than predicted by equation 3, especially at high levels of DEA (Fig. 2).

Discussion

The results illustrate the roles of geomorphology and land use as regional scale controllers of denitrification in SLM. Geomorphology strongly influences soil texture, which influences variation in denitrification and other biological processes at the landscape scale (Swanson *et al.* 1988, Groffman

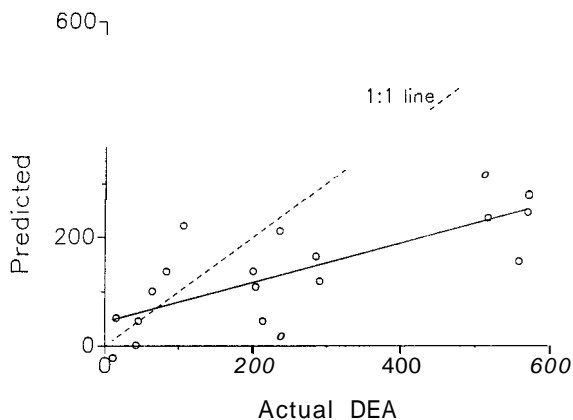


Fig. 2. Denitrification enzyme activity (DEA, $\text{ng N g}^{-1} \text{h}^{-1}$) predicted from equation 3 versus DEA measured in 22 soils over SLM, June 1986.

and Tiedje 1989a). Thus, the nature and distribution of different landforms influences the magnitude and distribution of regional scale denitrification activity. For example, the region to the north of SLM, which is dominated by sandy plain, would likely have a much lower potential for denitrification than SLM, while the regions to the south (Indiana and Ohio), which have large areas of clay lake plain and fine-textured glacial till, would likely have denitrification potential similar to SLM.

Land use effects on regional forest denitrification are related to the suitability of different soils for intensive agriculture. The poor water and nutrient holding capacity of sandy soils make them less suitable for row crop production than finer-textured soils. As a result, almost 50% of the regional forest occurs on sandy soils with very low denitrification capacity.

Agricultural land use affects forest denitrification through the export of NO_3^- from fertilized fields in surface runoff and groundwater flow to adjacent forest areas. The highest denitrification rates that we measured in our landscape scale study were in poorly drained fine-textured soils adjacent to agricultural fields. Movement of NO_3^- from agricultural uplands to lowland forests likely increases the contribution of fine-textured soils to regional forest denitrification since most uplands are cultivated in fine-textured landscapes. Con-

versely, most sandy uplands are not cultivated and most sandy lowland areas do not receive inputs of agriculturally derived NO_3^- . Thus, the small contribution of sandy soils to regional forest denitrification in SLM may be due to a combination of factors. The poorly drained sandy soils in our study had low denitrification relative to the finer textured soils likely due to the inherent nature of the N cycle in these soils (Groffman and Tiedje 1989b), *and* to the lack of NO_3^- inputs from cultivated upland areas. Poorly drained sandy soils receiving large amounts of NO_3^- could potentially support high rates of denitrification. This potential should be considered and quantified in sandy landscapes with intensively cultivated uplands.

Regional scale estimates of denitrification are useful in a water quality context. Nitrate concentrations in the Grand River, the main drainage system in SLM, have increased significantly in recent years, coincident with large increases in N fertilizer use (Smith *et al.* 1987; Lowrance and Groffman 1987). The role of denitrification in mitigating the water quality effects of fertilizer use will differ from region to region based on the land use and geomorphological factors discussed above. Regional denitrification analyses may be useful for evaluating the ability of different regions to support intensive agricultural activities without degradation of water quality.

The regional scale analysis clearly shows the usefulness of systematic stratification for large scale biogeochemical studies. If we had attempted to choose a 'representative' site to estimate the contribution of SLM to the global N budget, we would have greatly underestimated rates if we had chosen a sandy site, and greatly overestimated rates if we had chosen a clay loam site.

Our experimental design stratified the region into nine functional groups based on soil texture and natural drainage. Each of the 64 soil series that occurs in the region was placed into one of these groups. Soil series are distinguished by specific pedological characteristics that may not create strong functional differences (Hole 1978; Bouma 1986). Wosten *et al.* (1985) grouped 110 soil mapping units into 41 functional classes for a soil water simulation modeling effort by analyzing physical

properties of the different series. We measured DEA across the region to test if our nine groups gave sufficient coverage of the range of conditions present.

Results from our validation sampling using DEA showed that the patterns of denitrification with soil texture and natural drainage that we observed at the landscape scale held up at the regional scale, and that extrapolation of data from our experimental sites was justified. The slopes in the multiple regression equations for sand and drainage index were similar in the regional and landscape-scale studies (comparing equations 3 and 4), and the r^2 values were also very similar. Measured DEA was higher than predicted in many cases. The prediction equation (equation 3) was developed using the annual mean of DEA. This mean was based on data from 9 sample dates in 1985, including summer dates with low levels of DEA. The validation sampling was done in June 1986, which was a time of relatively high DEA in 1985, so it is not surprising that the measured DEA was higher than predicted. Future validation efforts with DEA should utilize more comprehensive temporal sampling to provide a better estimate of annual DEA levels.

The conceptual basis for using DEA as a validation variable is based on the persistence of denitrification enzymes in soil during periods unfavorable for denitrification activity (Smith and Parsons 1985; Groffman 1987; Martin *et al.* 1988). Due to this persistence, DEA varies very little over the course of the year relative to parameters such as hourly denitrification rate, soil moisture or soil NO_3^- (Groffman and Tiedje 1989b). As a result, there is usually a very poor relationship between DEA and hourly or daily denitrification rate. Denitrification enzyme level is a parameter that is likely the long term product of multiple soil and ecosystem factors, similar to soil organic matter level or microbial biomass carrying capacity (van Veen *et al.* 1984). This type of parameter is likely to be a better predictor of annual fluxes than daily or hourly fluxes. A similar relationship between inherent soil 'potential' measurements and actual fluxes was shown by Matson and Vitousek (1987), who found strong relationships between potential rates of N mineralization and nitrification and N_2O flux

in a range of tropical soils. Further testing of the strength of the relationship between annual denitrification N loss and DEA is necessary to assess the ultimate usefulness of DEA as a validation tool for regional scale extrapolations.

The value of our regional scale estimates are limited because we only addressed one land use type (forest) and we did not address year-to-year variation in activity. Our field scale studies showed that over 80% of the annual denitrification activity occurred during brief periods of high soil wetness during early spring and late fall (Groffman and Tiedje 1989a). In north temperate regions, there is a high annual constancy to these wet periods due to accumulation of snow during the winter and a lack of plant uptake of water during early spring and late fall (Creemens and Mokma 1986). Thus, year-to-year variation in annual N loss to denitrification from forest soils is probably much lower than season-to-season variation within a year. Studies in grassland found that annual variations in N_2O flux were much less than daily or seasonal variations (Parton *et al.* 1988). We intend to expand our studies to address annual variation in annual N loss to denitrification and to include other land use and biome types.

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