Nitrogen Attenuation in Wetlands: A Literature Review Bibliography with Abstracts and Annotations

Final Report

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1.0 FORESTED WATERSHEDS

Aber, J.D., Magill, A. Boone, R., Melillo, J.M., Steudler, P. and R. Bowden. 1993. Plant and soil responses to chronic nitrogen additions at the Harvard Forest, Massachusetts. Ecological Applications 3(1), pp. 156-166.

Abstract. Data are presented on changes in plant and soil processes in two forest types (red pine plantation and oak–maple forest) at the Harvard Forest, Petersham, Massachusetts, in response to 3 yr of chronic N fertilization. The hardwood stand exhibited greater N limitation on biological function than the pine stand prior to fertilization as evidenced by a lower net N mineralization rate, nearly undetectable rates of net nitrification, and very low foliar N content.

N additions were made in six equal applications throughout the growing season, and consisted of 5 and 15 $g \cdot m^{-2} \cdot yr^{-1}$ of N as ammonium nitrate. The pine stand showed larger changes than the hardwood stand for extractable N, foliar N, nitrification, and N leaching loss. Retention of added N was essentially 100% for all but the high application pine plot from which significant N leaching occurred in the 3rd yr of application. From 75 to 92% of N added to fertilized plots was retained in the soil, with larger fractions retained in the hardwood stand than the pine stand for all treatments.

As hypothesized, the stands are exhibiting highly nonlinear patterns of nitrogen output in response to continuous nitrogen inputs. The implications of this nonlinearity for regional eutrophication of surface waters and atmospheric deposition control policy are discussed.

Aber, J.D., Magill, A., McNulty, S.G., Boone, R.D., Nadelhoffer, K.J., Downs M., and R. Hallett. 1995. Forest biogeochemistry and primary production altered by nitrogen saturation. *Water, Air, and Soil Pollution* 85, pp. 1665-1670.

Abstract not available in electronic format.

Aber, J.D., Melilo, J.M., Nadelhoffer, K.J., Pastor J., and R.D. Boone. 1991. Factors controlling nitrogen cycling and nitrogen saturation in northern temperate forest ecosystems. *Ecological Applications* 1(3), pp. 303-315.

Abstract. An analysis of the factors controlling rates of nitrogen cycling in northern temperate forest ecosystems is presented based on a quantitative analysis of an extensive data set for forests in Wisconsin and Massachusetts as those data are synthesized in a computer model (VEGIE) of organic matter and nutrient dynamics. The model is of the "lumped-parameter," nutrient-flux-density type, dealing with major components of forest ecosystems rather than stems or species. It deals explicitly with the interactions among light, water, and nutrient availability in determining transient and equilibrium rates of primary production and nutrient cycling. Data are presented for parameterizing the plant component of the system at either the species or community level.

A major conclusion is that the ultimate control on equilibrium nitrogen-cycling rates resides not within the nitrogen cycle itself (for example in litter quality or net primary production [NPP] allocation patterns) but rather in ratios of resource-use efficiency by vegetation as compared with the ratios of resource availability. Litter quality and allocation patterns, along with rates of N deposition, do affect the rate at which a system approaches the equilibrium cycling rate. The model is used to explain observed variation in nitrogen-cycling rates among forest types, and to predict the timing and occurrence of "nitrogen saturation" (N availability in excess of biotic demand) as a function of nitrogen deposition rates and harvesting.

Aber, J.D., McDowell, W., Nadelhoffer, K.J., Magill, A., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L., and I. Fernandez. 1998. Nitrogen saturation in forest ecosystems: hypotheses revisited. *Bioscience* 48(11), pp. 921-934.

Abstract: None available, first page of article as follows:

Nitrogen emissions to the atmosphere due to human activity remain elevated in industrialized regions of the world and are accelerating in many developing regions (Galloway 1995). Although the deposition of sulfur has been reduced over much of the United States and Europe by aggressive environmental protection policies, current nitrogen deposition reduction targets in the US are modest. Nitrogen deposition remains relatively constant in the northeastern United States and is increasing in the Southeast and the West (Fenn et al. in press).

Recent research raises questions on the processes of N retention in soils, and how much protection these processes offer to forest and stream ecosystems

The US acid deposition effects program in the 1980s (the National Atmospheric Precipitation Assessment Program, or NAPAP) funded research mostly on the effects of sulfur deposition rather than on those associated with nitrogen. Since the completion of this program and the passage of the 1990 Clean Air Act Amendments, the US regulatory community has not supported substantial additional research on acidic deposition. Consequently, the potential for nitrogen deposition to contribute to soil and surface water acidification remains unresolved. Unlike the European Community, which has pursued an active and well-coordinated international program on nitrogen deposition effects (the NITREX program; Wright and van Breeman 1995, Wright and Rasmussen 1998) and on critical loads for nitrogen (Nilsson and Grennfelt 1988, Henricksen et al. 1992, Warfvinge and Sverdrup 1992, Wright and Rasmussen 1998), research on this topic in the United States remains scattered and piecemeal. Policy and regulatory activity have also, until very recently, been virtually nonexistent.

Despite this lack of support and direction, the US scientific community has continued to express concern over the long-term effects of nitrogen deposition on forests, grasslands, streams, and estuaries (e.g., Aber et al. 1995, Wedin and Tilman 1996, Asner et al. 1997, Vitousek et al. 1997, Fenn et al. in press). These concerns cover the deposition not only of oxides of nitrogen (NO_x and especially nitrate, NO_3^-), which originate mainly from fossil fuel combustion, but also of ammonium (NH_4^+), which originates from the production and use of fertilizers in agriculture. In parts of Europe and much of Asia, deposition of ammonium exceeds that of nitrate, sometimes by severalfold (Galloway 1995).

In 1989, we published a review in *BioScience* of the known effects of nitrogen deposition on temperate forest ecosystems in which we set forth a series of hypotheses about the long-term consequences of continuously elevated nitrogen inputs (Aber et al. 1989). We stressed the potential for nitrogen additions to lead to nitrate and aluminum mobility in soils, causing soil and stream acidification, nutrient:nitrogen imbalances in trees, and forest decline. The integrated set of hypotheses (Figure 1) suggested that responses to nitrogen deposition would not be linear and would therefore not be captured in simple dose–response functions. Rather, we expected them to be highly nonlinear, with critical thresh-

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Annotation:

- Forested watershed study
- Information drawn from various sites
- Overview article based on information from prior studies of N retention and fertilization of forested watersheds
- No data presented

This theoretical review article describes the evolution of hypotheses regarding the main pathway of N assimilation and retention in forest ecosystems exposed to chronically elevated nitrogen inputs. Ecosystem response to increased nitrogen additions was described, with four stages of N saturation defined as follows:

- Stage 0: inputs of N from atmospheric sources are at background levels and watershed losses of N are negligible. Normal stand progression.
- Stage 1: increased deposition of N; adverse effects on terrestrial ecosystem not evident. A fertilization effect results in increased ecosystem production and tree vigor. Retention of N is very efficient and little or no N is lost annually to surface waters that drain the watershed.
- Stage 2: Subtle, nonvisual effects occur. Fine root mass decreases, foliar biomass decreases, and net primary production decreases relative to stage 1. Nitrate assimilation may increase at this stage. The phase between Stage 1 and 2 is called nitrogen saturation.
- Stage 3: Net primary production, foliar biomass, and nitrate assimilation decrease at this phase while foliar N concentration increases; ecosystem decline is evident. Nitrate leaching and N_2O emission increase. The most advanced stages of N saturation were seen in regions with the most elevated rates of N deposition.

The initial hypothesis was that plant uptake would be the main sink for atmospherically derived N, resulting in increased photosynthesis and tree growth, with recycling of N through litter and humus to the available pool. This mechanism would saturate quickly, resulting in early increases in nitrate leaching. However, later studies showing very high N retention in soils led scientists to question the assumption that free-living soil microbes were carbon or energy limited.

The revised hypothesis includes analysis of Ca:Al and Mg:N ratios in foliage and reduction in nitrogen mineralization during the third stage in the process of nitrogen saturation. Microrhyzal assimilation and exudation of N is thought to be the dominant process underlying immobilization of added N to these systems. The revised hypothesis suggests previous land use history defines the initial stages of N saturation, and that deciduous stands move more slowly toward N saturation than evergreen stands.

Aber, J.D., Nadelhoffer, K.J., Steudler P., and J. Melillo. 1989. Nitrogen saturation in temperate forest ecosystems. *Bioscience* 39(6), pp. 921-933.

No abstract.

Brief description: Nitrogen cycling and N saturation in forested watersheds are discussed. N saturation is seen to occur in stages as above. Implications for surface water, in particular nutrient leaching, are discussed.

Aber, J.D., Ollinger S.V., and C.T. Driscoll. 1996. Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. *Ecological Modeling* 101, pp. 61-78.

Abstract

A generalized, lumped-parameter model of carbon (C), water, and nitrogen (N) interactions in forest ecosystems (PnET-CN) is presented. The model operates at a monthly time step and at the stand-to-watershed scale, and is validated against data on annual net primary productivity, monthly carbon and water balances, annual net N mineralization, nitrification, foliar N concentration and annual and monthly N leaching losses for two sites, Hubbard Brook (West Thornton, NH) and Harvard Forest (Petersham, MA). It is then used to predict transient responses in function resulting from changes in land use and N deposition, as well as the maximum rate of N cycling which can be sustained for any given combination of site, climate and species. Model predictions suggest a very long legacy effect of land use history on N cycling. Even with only one 'active' soil organic matter pool, complete recovery from three modest harvests at Hubbard Brook is predicted to require more than two centuries at current N deposition rates. Complete recovery is predicted to take even longer at the Harvard Forest where biomass removals have been more intense. PnET-CN is used to predict maximum sustainable rates of N cycling for 14 sites throughout the northeastern USA. Predicted maximum values were higher, as expected, than measured N mineralization rates for all but one site. The measured fraction of N mineralization nitrified at these 14 sites showed a general relationship with the ratio of measured to maximum net N mineralization. This latter ratio is discussed as a potentially useful indicator of the degree of nitrogen saturation in forest ecosystems. A regional map of predicted maximum N cycling rates is presented based on regressions between model predictions and summary climatic variables.

Addy, K.L., Gold, A. J., Groffman, P. M., and P. A. Jacinthe. 1999. Ground Water Nitrate Removal in Subsoil of Forested and Mowed Riparian Buffer Zones. *Journal of Environmental Quality* 28, pp. 962-970.

Abstract:

We studied two similar riparian sites in southern New England and examined ground water nitrate (NO_3--N) removal in the subsurface of mowed (i.e., herbaceous) vs. forested (i.e., woody) vegetation. Each site consisted of poorly drained, fine to medium sands and contained adjacent areas of mowed and forested vegetation. We dosed mesocosms with bromide and lSN labeled NO_3-N amended ground water to simulate the shallow ground water NO_3-N dynamics of riparian buffer zones. Mesocosms were composed of undisturbed, horizontal soil cores (40 cm long, 15 cm diameter) extracted from seasonally saturated subsoil. We observed substantial ground water NO_3-N removal and denitrification at all locations. Ground water NO_3--N removal rates were significantly correlated with carbon-enriched patches of organic matter. This correlation supports previous work that patches function as *hotspots* of microbial activity in the subsoil. Within each site, we found no significant difference in ground water NO_3-N removal rates in the subsoil of forested and mowed areas and we noted tree roots throughout the subsoil of the mowed areas. We found that ground water NO_3-N removal rates differed significantly between similar sites. We caution against ascribing specific ground water NO_3-N removal rates to different riparian aboveground vegetation types without recognizing the importance of site differences, e.g., water table dynamics, land use legacy and adjacent vegetation. Riparian zones composed of a mix of forested and mowed vegetation, common in agroforestry and suburban land uses, may remove substantial amounts of ground water NO_3-N.

Annotation:

- Forested and mowed riparian areas
- North Kingstown, Rhode Island
- Mesocosm experiments
- Provides data on denitrification potential, NO_3, NH_4^+ sediment organic matter

Previous studies have shown high variation in NO_3-N removal in grassed riparian vs. forested riparian sites. This study compared the two in laboratory mesocosm experiments. No significant difference in ground water NO_3-N removal rates within the subsoil of forested and mowed riparian areas was found.

However there were significant differences in ground water NO_3-N removal rates between two riparian sites with similar soil texture, drainage class, and morphology.

Implications for riparian buffer zones for ground water NO_3-N removal include the following:

- A large difference in aboveground vegetation (i.e. forested vs. mowed areas) doesn't necessarily mean belowground microbial processes differ.
- Although aboveground vegetation is strikingly different, the composition and distribution of roots may not directly reflect the aboveground vegetation.
- Belowground biomass of mowed, herbaceous buffers adjacent to or intermixed with trees may represent a composite of roots and function similarly to forested buffer zones.
- Land use legacy: cultivation and plowing in of organic matter during farming for 20 yr may increase soil organic carbon content in deeper layers. This can affect denitrification rates.
- Vegetation effect: presence of nitrogen fixing species may affect denitrification rates. Site B was dominated by Speckled Alder, an N fixer; site A by red maple, which can't fix N. Site B showed higher denitrification potential.

The author's caution against ascribing specific ground water NO_3-N removal rates to different aboveground riparian vegetation types without recognizing the importance of other site differences including water table dynamics, land use legacy, and adjacent vegetation.

Berntson, G.M. and J.D. Aber. 2000. Fast nitrate immobilization in N saturated temperate forest soils. *Soil Biology and Biochemistry* 32, pp. 151-156.

Abstract:

Recent application of ^{15}N pool dilution techniques has suggested that gross nitrate immobilization rates in temperate forest soils with low N deposition may be significantly greater than previously thought. In contrast, there are some data that suggest forest soils, which have received high N-deposition, may not immobilize NO_3. Such studies do not include quantification of the relative importance of fast and slow immobilization of NO_3. We have examined the kinetics of NO3ÿ immobilization in two temperate forest soils exposed to a range of experimental N deposition. We found that the greatest potential for NO_3 immobilization in these soils was by a fast process of immobilization and only the hardwood forest with low (ambient) N deposition showed any significant slow NO3ÿ immobilization (typically equated with microbial immobilization). High N additions have resulted in the loss of the slow immobilization process and a reduction in the amount of fast immobilization. The patterns of NO_3 immobilization we report are important for two reasons. First, they demonstrate that immobilization of N, which exhibits rapid kinetics, may play an important part in regulating the N retention capacity of forests in response to N deposition. Second, they suggest that current models which include only the slower phase of N immobilization may be inaccurate representations of N immobilization processes in soils.

Bischoff , J.M., Bukaveckas, P., Mitchell M.J., and T. Hurd. 2001. N Storage and cycling in vegetation of a forested wetland: implications for watershed N processing. *Water, Air, and Soil Pollution* 128, pp. 97-114.

Abstract not available in electronic format.

Brettar, I. and M.G. Hofle. 2002. Close correlation between the nitrate elimination rate by denitrification and the organic matter content in hardwood forest soils of the upper Rhine floodplain (France). *Wetlands* 22(2), pp. 214-224.

- Forested wetland
- Rhinau, France
- Laboratory study
- Reports data on NO_3, NH_4, TN, oxygen content, redox potential, denitrification rates, organic content, temperature, pH

Abstract:

Denitrification is a major process for reducing the nitrogen load in floodplains. Soil samples from depth profiles of a hardwood forest of the floodplain of the Upper Rhine were analyzed for their potential to denitrify under permanent nitrate supply. The soils were silty to silty-clayey in the surface layer and had increasing sand content with depth. The rate of denitrification was greatest in top soil and decreased with depth. Organic matter content along profiles decreased exponentially with depth. The denitrification rate showed a very close correlation with the organic matter content of the hardwood forest soil. A denitrification rate of 0.57 mg N day^{-1} g^{-1} organic matter present in the soil was calculated for all depths and sites and was constant for up to 23 days. This rather straightforward relationship may support predictions of the (maximum) potential denitrification rates *in situ*. Furthermore, this relationship may support modeling of the nitrogen balance and contribute to an efficient flood management strategy for the restored floodplains of the Upper Rhine in order to support nitrate removal by denitrification.

Annotation:

Study evaluated denitrification potential in laboratory experiments under conditions of permanent nitrate supply. Found a close correlation between organic carbon content and denitrification potential.

Implications for nitrogen retention in wetlands:

- Organic matter content in soils influences denitrification rates when environmental conditions are optimal (nitrate availability, appropriate temperature, low oxygen concentration)
- Environmental conditions change over small spatial scales and denitrification rates will vary on similar scales

Campbell, J.L., Hornbeck, J.W., Mitchell, M.J., Adams, M., Castro, M.S., Driscoll, C.T., Kahl, J.S., Kochenderfer, J.N., Likens, G.E., Lynch, J.A., Murdoch, P.S., Nelson, S.J., and J.B. Shanley. 2004. Input-output budgets of inorganic nitrogen for 24 forest watersheds in the northeastern United States: a review. *Water, Air, and Soil Pollution* 151, pp. 373-396.

- Forested watershed
- Various locations in the northeastern United States
- Literature Review
- No new data presented

Abstract:

Input-output budgets for dissolved inorganic nitrogen (DIN) are summarized for 24 small watersheds at 15 locations in the northeastern United States. The study watersheds are completely forested, free of recent physical disturbances, and span a geographical region bounded by West Virginia on the south and west, and Maine on the north and east. Total N budgets are not presented; however, fluxes of inorganic N in precipitation and streamwater dominate inputs and outputs of N at these watersheds. The range in inputs of DIN in wet-only precipitation from nearby National Atmospheric Deposition Program (NADP) sites was 2.7 to 8.1 kg N ha^{-1} yr^{-1} (mean = 6.4 kg N ha^{-1} yr^{-1}; median = 7.0 kg N ha^{-1} yr^{-1}). Outputs of DIN in streamwater ranged from 0.1 to 5.7 kg N ha^{-1} yr^{-1} (mean = 2.0 kg N ha^{-1} yr^{-1}; median = 1.7 kg N ha^{-1} yr^{-1}). Precipitation inputs of DIN exceeded outputs in streamwater at all watersheds, with net retention of DIN ranging from 1.2 to 7.3 kg N ha^{-1} yr^{-1} (mean = 4.4 kg N ha^{-1} yr^{-1}; median = 4.6 kg N ha^{-1} yr^{-1}). Outputs of DIN in streamwater were predominantly NO_3-N (mean = 89%; median = 94%). Wet deposition of DIN was not significantly related to DIN outputs in streamwater for these watersheds. Watershed characteristics such as hydrology, vegetation type, and land-use history affect DIN losses and may mask any relationship between inputs and outputs. Consequently, these factors need to be included in the development of indices and simulation models for predicting 'nitrogen saturation' and other ecological processes.

Annotation:

The authors state that the objectives of this review analysis were to establish ranges for fluxes of inorganic nitrogen (ammonium and nitrate) in precipitation and streamwater and to determine if there are general spatial patterns in nitrogen retention across the northeastern United States. This objective meets the needs for the MA DEP nitrogen attenuation study for forested watersheds, and was therefore chosen for this bibliography.

The review provides great detail and data about the climate conditions, vegetation, land-use, hydrology, geology, and water chemistry for all sites. Source-sink budgets (inputs-outputs) for ammonium, nitrate, and dissolved inorganic nitrogen (DIN) were created based upon these data, which are compiled in the text's tables. Loss of nitrogen (inputs > outputs) from the investigated watersheds was defined as retention; Table III presents the nitrogen inputs, outputs, and retention percentage. Results indicated that most watersheds retained nitrate on an annual basis, with rates ranging from 700 to 35,700 µmol N m^{-2} yr^{-1},with streamwater (output) concentrations of nitrate generally lower than those in precipitation (input). Of course, these forested watersheds do not receive the degree of excess nitrogen loading that coastal areas do. Groundwater was not monitored or included in the nitrogen budgets- this could have an important influence on the nitrogen budgets, cycling, and transport (such as indicated in McHale et al., 2002). Despite the fact that nitrogen attenuation was occurring in most watersheds (all but one investigated), there was a large range in retention percentage. As one of the main objectives for this research the authors examined the more intensively monitored sites to determine the factors affecting nitrogen retention (hydrology, vegetation, land-use/fire), though no conclusive factors were stated. The value of this paper lies in the detailed organization of data compiled for watersheds, and the general characterizations of nitrogen transport.

Compton, J.E., Boone, R.D., Motzkin G., and D.R. Foster. 1998. Soil carbon and nitrogen in a pine-oak sand plain in central Massachusetts: role of vegetation and land use history. *Oecologia* 116, pp. 536-542.

Abstract not available in electronic format.

Currie, W.S. and K.J. Nadelhoffer. 1999. Dynamic redistribution of isotopically labelled cohorts of nitrogen in two temperate forests. Ecosystems 2, pp. 4-18.

Abstract:

We compared simulated time series of nitrogen-15 (^{15}N) redistribution following a large-scale labeling experiment against field recoveries of $^{15}NH_4^+$ and $^{15}NO_3^-$ in vegetation tissues. We sought to gain insight into the altered modes of N cycling under long-term, experimentally elevated N inputs. The study took place in two contrasting forests: a red pine stand and a mixed deciduous stand (predominantly oak) at the Harvard Forest, Massachusetts, USA. We used TRACE, a dynamic simulation model of ecosystem biogeochemistry that includes $^{15}N/^{14}N$ ratios in N pools and fluxes. We simulated input–output and internal fluxes of N, tracing the labeled cohorts of N inputs through ecosystem pools for one decade. TRACE simulated the peaks and timing of ^{15}N recovery in foliage well, providing a key link between modeling and field studies. Recovery of tracers in fine roots was captured less well. The model was structured to provide rapid, initial sinks for $^{15}NO_3^-$ and $^{15}NH_4^+$ in both forests, as indicated by field data. In simulations, N in litter turned over rapidly, even as humus provided a long-term sink for rapidly cycling N. This sink was greater in the oak forest. Plant uptake fluxes of N in these fertilized plots were on the same order of magnitude as net assimilation fluxes in forest-floor humus. A striking result was the small rate of incorporation of N in humus resulting from the transfer of litter material to humus, compared with large fluxes of N into humus and its associated microorganisms through direct transfers from pools of inorganic N in soils.

Key words: tracer; simulation model; biogeochemistry; decomposition; humification; immobilization; nutrient cycling; nitrogen saturation; turnover; forest floor; synthesis.

Currie, W.S. and K.J. Nadelhoffer. 2002. The imprint of land use history: patterns of carbon and nitrogen in downed woody debris at the Harvard Forest. *Ecosystems* 5, pp. 446-460.

Abstract:

Few data sets have characterized carbon (C) and nitrogen (N) pools in woody debris at sites where other aspects of C and N cycling are studied and histories of land use and disturbance are well documented. We quantified pools of mass, C, and N in fine and coarse woody debris (CWD) in two contrasting stands: a 73-year-old red pine plantation on abandoned agricultural land and a naturally regenerated deciduous forest that has experienced several disturbances in the past 150 years. Masses of downed woody debris amounted to 40.0 Mg ha^{-1} in the coniferous stand and 26.9 Mg ha^{-1} in the deciduous forest (20.4 and 13.8 Mg C ha^{-1}, respectively). Concentrations of N were higher and C:N ratios were lower in the deciduous forest compared to the coniferous. Pools of N amounted to 146 kg N ha^{-1} in the coniferous stand and 155 kg N ha^{-1} in the deciduous forest; both are larger than previously published pools of N in woody debris of temperate forests. Woody detritus buried in O horizons was minimal in these forests, contrary to previous findings in forests of New England. Differences in the patterns of mass, C, and N in size and decay classes of woody debris were related to stand histories. In the naturally regenerated deciduous forest, detritus was distributed across all size categories, and most CWD mass and N was present in the most advanced decay stages. In the coniferous plantation, nearly all of the CWD mass was present in the smallest size class (less than 25 cm diameter), and a recognizable cohort of decayed stems was evident from the stem-exclusion phase of this even-aged stand. These results indicate that heterogeneities in site histories should be explicitly included when biogeochemical process models are used to scale C and N stocks in woody debris to landscapes and regions.

Dail, D.B., Davidson E.A., and J. Chorover. 2001. Rapid abiotic transformation of nitrate in an acid forest soil. *Biogeochemistry* 54, pp. 131–146.

Abstract:

Nitrate immobilization into organic matter is thought to require catalysis by the enzymes of soil microorganisms. However, recent studies suggest that nitrate added to soil is immobilized rapidly and this process may include abiotic pathways. We amended living and sterilized soil with ^{15}N-labeled nitrate and nitrite to investigate biotic and abiotic immobilization. We report rapid transformation of nitrate in incubations of the O layer of forest soils that have been sterilized to prevent microbial activity and to denature microbial enzymes. Approximately 30, 40, and 60% of the ^{15}N-labeled nitrate added to live, irradiated, or autoclaved organic horizon soil disappeared from the extractable inorganic-N pool in less than 15 minutes. About 5% or less of the nitrate was recovered as insoluble organic N in live and sterilized soil, and the remainder was determined to be soluble organic N. Added ^{15}N-nitrite, however, was either lost to gaseous N or incorporated into an insoluble organic N form in both live and sterile organic soils. Hence, the fate and pathway of apparent abiotic nitrate immobilization differs from the better-known mechanisms of nitrite reactions with soil organic matter. Nitrate and nitrite added to live A-horizon soil was largely recovered in the form added, suggesting that rapid conversion of nitrate to soluble organic-N may be limited to C-rich organic horizons. The processes by which this temperate forest soil transforms added nitrate to soluble organic-N cannot be explained by established mechanisms, but appears to be due to abiotic processes in the organic horizon.

Fenn, M.E., Poth, M.A., Aber, J.D., Baron, J.S., Bormann, B.T., Johnson, D.W., Lemly, A.D., McNulty, S.G., Ryan, D.F., and R. Stottlemyer. 1998. Nitrogen excess in North American ecosystems: Predisposing factors, ecosystem responses, and management strategies. *Ecological Applications* 8(3), pp. 706-733.

Abstract. Most forests in North America remain nitrogen limited, although recent studies have identified forested areas that exhibit symptoms of N excess, analogous to overfertilization of arable land. Nitrogen excess in watersheds is detrimental because of disruptions in plant/soil nutrient relations, increased soil acidification and aluminum mobility, increased emissions of nitrogenous greenhouse gases from soil, reduced methane consumption in soil, decreased water quality, toxic effects on freshwater biota, and eutrophication of coastal marine waters. Elevated nitrate (NO_3^-) loss to groundwater or surface waters is the primary symptom of N excess. Additional symptoms include increasing N concentrations and higher N:nutrient ratios in foliage (i.e., N:Mg, N:P), foliar accumulation of amino acids or NO_3^-, and low soil C:N ratios. Recent nitrogen-fertilization studies in New England and Europe provide preliminary evidence that some forests receiving chronic N inputs may decline in productivity and experience greater mortality. Long-term fertilization at Mount Ascutney, Vermont, suggests that declining and slow N-cycling coniferous stands may be replaced by fast-growing and fast N-cycling deciduous forests.

Symptoms of N saturation are particularly severe in high-elevation, nonaggrading spruce–fir ecosystems in the Appalachian Mountains and in eastern hardwood watersheds at the Fernow Experimental Forest near Parsons, West Virginia. In the Los Angeles Air Basin, mixed conifer forests and chaparral watersheds with high smog exposure are N saturated and exhibit the highest streamwater NO_3^- concentrations for wildlands in North America. High-elevation alpine watersheds in the Colorado Front Range and a deciduous forest in Ontario, Canada, are N saturated, although N deposition is moderate ($\sim$8 $kg \cdot ha^{-1} \cdot yr^{-1}$). In contrast, the Harvard Forest hardwood stand in Massachusetts has absorbed >900 kg N/ha during 8 yr of N amendment studies without significant NO_3^- leaching, illustrating that ecosystems vary widely in the capacity to retain N inputs.

Overly mature forests with high N deposition, high soil N stores, and low soil C:N ratios are prone to N saturation and NO_3^- leaching. Additional characteristics favoring low N retention capacity include a short growing season (reduced plant N demand) and reduced contact time between drainage water and soil (i.e., porous coarse-textured soils, exposed bedrock or talus). Temporal patterns of hydrologic fluxes interact with biotic uptake and internal cycling patterns in determining ecosystem N retention. Soils are the largest storage pool for N inputs, although vegetation uptake is also important. Recent studies indicate that nitrification may be widespread in undisturbed ecosystems, and that microbial assimilation of NO_3^- may be a significant N retention mechanism, contrary to previous assumptions. Further studies are needed to elucidate the sites, forms, and mechanisms of N retention and incorporation into soil organic matter, and to test potential management options for mitigating N losses from forests. Implementation of intensive management practices in N-saturated ecosystems may only be feasible in high-priority areas and on a limited scale. Reduction of N emissions would be a preferable solution, although major reductions in the near future are unlikely in many areas due to economic, energy-use, policy, and demographic considerations.

Flite O.P. III, Shannon, R.D., Schnabel, R.R., and Richard R. Parizek. 2001. Nitrate removal in a riparian wetland of the Appalachian Valley and Ridge physiographic province. *Journal of Environmental Quality* 30, pp. 254–261.

Abstract:

Riparian zones within the Appalachian Valley and Ridge physiographic province are often characterized by localized variability in soil moisture and organic carbon content, as well as variability in the distribution of soils formed from alluvial and colluvial processes. These sources of variability may significantly influence denitrification rates. This investigation studied the attenuation of nitrate (NO_3) as wastewater effluent flowed through the shallow ground water of a forested headwater riparian zone within the Appalachian Valley and Ridge physiographic province. Ground water flow and NO_3 measurements indicated that NO_3 discharged to the riparian zone preferentially flowed through the A and B horizons of depressional wetlands located in relic meander scars, with NO_3 decreasing from >12 to <0.5 mg L^{-1}. Denitrification enzyme activity (DEA) attributable to riparian zone location, soil horizon, and NO_3 amendments was also determined. Mean DEA in saturated soils attained values as high as 210 g N kg^{-1} h^{-1}, and was significantly higher than in unsaturated soils, regardless of horizon ($p < 0.001$). Denitrification enzyme activity in the shallow A horizon of wetland soils was significantly higher ($p < 0.001$) than in deeper soils. Significant stimulation of DEA ($p < 0.027$) by NO_3 amendments occurred only in the meander scar soils receiving low NO_3 (<3.6 mg L^{-1}) concentrations. Significant denitrification of high NO_3 ground water can occur in riparian wetland soils, but DEA is dependent upon localized differences in the degree of soil saturation and organic carbon content.

Goodale, C.L., Lajtha, K., Nadelhoffer, K.J., Boyer E.W., and N.A. Jaworski. 2002. Forest nitrogen sinks in large eastern U.S. watersheds: estimates from forest inventory and an ecosystem model. *Biogeochemistry* 57/58, pp. 239–266,

Abstract:

The eastern U.S. receives elevated rates of N deposition compared to preindustrial times, yet relatively little of this N is exported in drainage waters. Net uptake of N into forest biomass and soils could account for a substantial portion of the difference between N deposition and solution exports. We quantified forest N sinks in biomass accumulation and harvest export for 16 large river basins in the eastern U.S. with two separate approaches: (1) using growth data from the USDA Forest Service's Forest Inventory and Analysis (FIA) program, and (2) using a model of forest nitrogen cycling (PnET-CN) linked to FIA information on forest age-class structure. The model was also used to quantify N sinks in soil and dead wood, and nitrate losses below the rooting zone. Both methods agreed that net growth rates were highest in the relatively young forests on the Schuylkill watershed, and lowest in the cool forests of northern Maine. Across the 16 watersheds, wood export removed an average of 2.7 kg N ha^{-1} yr^{-1} (range: 1–5 kg N ha^{-1} yr^{-1}), and standing stocks increased by 4.0 kg N ha^{-1} yr^{-1} (–3 to 8 kg N ha^{-1} yr^{-1}). Together, these sinks for N in woody biomass amounted to a mean of 6.7 kg N ha^{-1} yr^{-1} (2–9 kg N ha^{-1} yr^{-1}), or 73% (15–115%) of atmospheric N deposition. Modeled rates of net N sinks in dead wood and soil were small; soils were only a significant net sink for N during simulations of reforestation of degraded agricultural sites. Predicted losses of nitrate depended on the combined effects of N deposition, and both short and long-term effects of disturbance. Linking the model with forest inventory information on age-class structure provided a useful step toward incorporating realistic patterns of forest disturbance status across the landscape.

Hill, A.R., Kemp, W.A., Buttle, J.M., and D. Goodyear. 1999. Nitrogen chemistry of subsurface storm runoff on forested Canadian Shield hillslopes. *Water Resources Research* 35(3), pp. 811-821.

- Forested watershed
- Dorset, Ontario, Canada
- Field and laboratory study
- Organic soil horizon in forests is a NO_3^- sink and can regulate inorganic N in runoff of forests

Abstract. The nitrogen dynamics of storm runoff was studied using throughfall trenches on slopes with thin soils in a white pine forest catchment near Dorset, Ontario. Hydrologic data were combined with analysis of isotopic signatures and nitrogen chemistry in throughfall, soil water, and hillslope runoff. Two hypotheses were tested: (1) macropore preferential flow pathways are a source of nitrate flushing in storm runoff, and (2) the nitrogen chemistry of subsurface storm flow is controlled by the mixing of event water fluxes via macropores with preevent soil water. Most flow occurred at the soil-bedrock interface on the slopes, and the use of ^{18}O indicated that a considerable fraction of event water moved vertically to bedrock via preferential flow paths. Despite high levels of inorganic N in throughfall, subsurface runoff N losses during autumn storms were dominated by dissolved organic nitrogen, and little nitrate flushing occurred via preferential flow paths. Comparisons of observed NO_3^- and NH_4^+ concentrations versus concentrations predicted from the mixture of event and preevent water in subsurface flow did not support hypothesis 2 and instead indicated depletion of inorganic N. Low rates of N mineralization and negligible nitrification in surface 0–0.1 m soil during June–October suggested high biological utilization of a limited soil N supply. Laboratory experiments in which soil cores were leached with solutions containing NO_3^- and bromide confirmed that the organic Ae horizon was a sink for NO_3^-. These data suggest that the biogeochemistry of the organic horizon can regulate patterns of inorganic N loss in subsurface runoff moving by preferential flow pathways in forest soils.

Annotation:

This paper presents a well designed investigation of stormwater runoff within a forested watershed dominated by white pine. The study area in Ontario, Canada is representative of a forest in Massachusetts. The study area was also the site of previous hydrologic investigations with provided valuable background information. The premise of this investigation was to monitor the nitrogen chemistry of water (surface and groundwater) as it passed through a forested catchment and to identify the processes responsible for any changes observed in N concentrations. Groundwater was analyzed in three distinct depths in the soil profile. Results indicated a consistent pattern of high initial concentration of nitrogen in storm (rain event) throughfall, followed by a decline to lower concentrations. This has been observed in other studies as well, and is indicative of a "flushing" of nitrogen accumulated in the soils. Comparisons of groundwater inorganic N concentrations indicated that the surface organic soil horizon (Ae) was a strong sink due to rapid microbial assimilation of the inorganic nitrogen and an absence of net nitrification. Nitrate concentrations below the Ae soil horizon at the soil-bedrock interface were often below the detection limit. At peak storm runoff at the soil-bedrock interface, nitrate concentrations peaked (although these were very low relative to surface concentrations), and declined thereafter. The nitrogen chemistry at depth was dominated by dissolved organic nitrogen (DON), with nitrate being microbially immobilized during percolation through the soil to the soil-bedrock interface (the preferential flowpath). The authors state in closing that this investigation clearly shows that the biogeochemistry of the surface organic layer is important in regulating inorganic N transport in subsurface storm runoff. This paper is one of the only identified in this literature search that specifically investigates the role of subsurface soil structure and its affect on nitrogen biogeochemistry.

Hunter, R.G. and S.P. Faulkner. 2001. Denitrification potentials in restored and natural bottomland hardwood wetlands. *Soil Science Society of America Journal* 65, pp. 1865-1872.

- Forested wetland
- Tensas River basin, Louisiana
- Field study
- Reports soluble organic carbon, denitrification potential, and soil moisture

Abstract not available in electronic format.

Annotation:

This study reports on a study of natural vs. restored bottomland hardwood wetlands. The one-year study looked at soil moisture, soluble organic carbon, and denitrification potential in replicated experiments. Denitrification potential was found to be about four times higher in natural wetlands (657 ng N_2O-N g^{-1} soil hr^{-1}) than in restored wetlands (167 ng N_2O-N g^{-1} soil hr^{-1}).

Ito, M., Mitchell, M.J., Driscoll C.T., and K.M. Roy. 2005. Nitrogen input-output budgets for lake-containing watersheds in the Adirondack Region in New York. *Biogeochemistry* 72, pp. 283-314.

Abstract. The Adirondack region of New York is characterized by soils and surface waters that are sensitive to inputs of strong acids, receiving among the highest rates of atmospheric nitrogen (N) deposition in the United States. Atmospheric N deposition to Adirondack ecosystems may contribute to the acidification of soils through losses of exchangeable basic cations and the acidification of surface waters in part due to increased mobility of nitrate (NO_3^-). This response is particularly evident in watersheds that exhibit 'nitrogen saturation.' To evaluate the contribution of atmospheric N deposition to the N export and the capacity of lake-containing watersheds to remove, store, or release N, annual N input–output budgets were estimated for 52 lake-containing watersheds in the Adirondack region from 1998 to 2000. Wet N deposition was used as the N input and the lake N discharge loss was used as the N output based on modeled hydrology and measured monthly solute concentrations. Annual outputs were also estimated for dissolved organic carbon (DOC). Wet N deposition increased from the northeast to the southwest across the region. Lake N drainage losses, which exhibited a wider range of values than wet N deposition, did not show any distinctive spatial pattern, although there was some evidence of a relationship between wet N deposition and the lake N drainage loss. Wet N deposition was also related to the fraction of N removed or retained within the watersheds (i.e., the fraction of net N hydrologic flux relative to wet N deposition, calculated as [(wet N deposition minus lake N drainage loss)/wet N deposition]). In addition to wet N deposition, watershed attributes also had effects on the exports of NO_3^-, ammonium (NH_4^+), dissolved organic nitrogen (DON), and DOC, the DOC/DON export ratio, and the N flux removed or retained within the watersheds (i.e., net N hydrologic flux, calculated as [wet N deposition less lake N drainage loss]). Elevation was strongly related with the lake drainage losses of NO_3^-, NH_4^+, and DON, net NO_3^- hydrologic flux (i.e., NO_3^- deposition less NO_3^- drainage loss), and the fraction of net NO_3^- hydrologic flux, but not with the DOC drainage loss. Both DON and DOC drainage losses from the lakes increased with the proportion of watershed area occupied by wetlands, with a stronger relationship for DOC. The effects of wetlands and forest type on NO_3^- flux were evident for the estimated NO_3^- fluxes flowing from the watershed drainage area into the lakes, but were masked in the drainage losses flowing out of the lakes. The DOC/DON export ratios from the lake-containing watersheds were in general lower than those from forest floor leachates or streams in New England and were intermediate between the values of autochthonous and allochthonous dissolved organic matter (DOM) reported for various lakes. The DOC/DON ratios for seepage lakes were lower than those for drainage lakes. In-lake processes regulating N exports may include denitrification, planktonic depletion, degradation of DOM, and the

contribution of autochthonous DOM and the influences of in-lake processes were also reflected in the relationships with hydraulic retention time. The N fluxes removed or stored within the lakes substantially varied among the lakes. Our analysis demonstrates that for these northern temperate lake-containing watershed ecosystems, many factors, including atmospheric N deposition, landscape features, hydrologic flowpaths, and retention in ponded waters, regulated the spatial patterns of net N hydrologic flux within the lake-containing watersheds and the loss of N solutes through drainage waters.

Jacinthe, P.A., Groffman, P.M., Gold, A.J., and A. Mosier. 1998. Patchiness in microbial nitrogen transformations in groundwater in a riparian forest. *Journal of Environmental Quality* 27, pp. 156-164.

- Forested riparian area
- Rhode Island, USA
- Field/lab (mesocosm study with cores from the field)
- Reports denitrification rate, total N, NH_4^+, NO_3^-, DON

Abstract:

We measured microbial N transformations in 15 cm diam. by 40 cm intact horizontal sections of aquifer material (mesocosms), taken from a riparian forest in Rhode Island, USA, incubated under ambient conditions. The mesocosms allowed us to measure these transformations on the same scale as hydrologic tracer methods (Br^-/NO_3^- ratios) that measure net NO_3^- removal. Our objective was to reconcile discrepancies between hydrologic tracer and microbial measurements in previous studies where laboratory-based microbial NO_3^- consumption measurements were much lower than in situ hydrologic measurements of net NO_3^- removal. We hypothesized that small "patches" of organic matter in the aquifer matrix, which are easily missed when sampling for microbial measurements, are "hotspots" of NO_3^- removal and are responsible for these discrepancies. Mesocosms were subjected to three treatments [Br^- only, Br^- + $^{15}NO_3^-$, Br^- + $^{15}NO_3^-$ + dissolved organic carbon (DOC)]. Solution (NH_4^+, NO_3^-, dissolved organic N) and gaseous (N_2O, $^{15}N_2O$, and $^{15}N_2$) inputs and outputs to the mesocosms were measured over a 132-d incubation, followed by destructive sampling for the presence of patches and residual ^{15}N in aquifer matrix and patch material. Total (gross) NO_3^- consumption by denitrification and immobilization was greater than net removal of NO_3^- measured by Br^-/NO_3^- ratios. Net NO_3^- consumption was only observed in mesocosms that contained "patches" of organic matter and was not increased by addition of DOC, suggesting that these patches, which represent <1% of aquifer weight, are critical to groundwater NO_3^- removal in riparian forests.

Annotation:

This mesocosm study was an effort to resolve discrepancies between field-scale studies of nitrogen removal from groundwater, and laboratory-scale studies of the processes (especially denitrification) underlying this nitrogen loss. Results showed that small patches of organic matter, which function as 'hotspots' for microbial activity (denitrification) are important in overall nitrogen uptake. The use of relatively large mesocosms, rather than microcosms allowed inclusion of organic matter patches so that the importance of these could be tested. The implication for this study is that subsurface organic matter content is important in determining the expected nutrient removal as groundwater passes through a wetland ecosystem.

Jacks, G., Joelsson, A., and S. Fleischer. 1994. Nitrogen retention in forested wetlands. *Ambio* 23(6), pp. 358-362.

- Forested wetlands
- Southern Sweden
- Field study
- Presents data on nitrogen in uplands, runoff, deposition, redox, and estimated N retention during the dormant season

Abstract not available electronically.

Annotation:

This study looks at forested wetlands as traps for nitrogen which may protect streams lakes and marine environments from eutrophication. The study established N budgets for six field sites in southwestern Sweden, and performed field studies of N2 and N2O emission from riparian soils at one site. Total nitrogen retention varied from -140 to 710 g ha-1 day-1 during the dormant season. During the growing season plant uptake balanced input so there was little or no output of N from these wetlands.

Lewis, W.M. 2002. Yield of nitrogen from minimally disturbed watersheds of the United States. *Biogeochemistry* 57/58, pp. 375-385.

Abstract. Watersheds of the US Geological Survey's Hydrologic Benchmark Network program were used in estimating annual yield of total nitrogen and nitrogen fractions (ammonium, nitrate, dissolved organic N, particulate N) in relation to amount of runoff, elevation, and watershed area. Only watersheds minimally disturbed with respect to the nitrogen cycle were used in the analysis (mostly natural vegetation cover, no point sources of N, atmospheric deposition of inorganic N < 10 kg ha^{-1} y^{-1}). Statistical analysis of the yields of total nitrogen and nitrogen fractions showed that elevation and watershed area bear no significant relationship to nitrogen yield for these watersheds. The yields of total nitrogen and nitrogen fractions are, however, strongly related to runoff ($r^2 = 0.91$ for total N). Annual yield increases as runoff increases, but at a rate lower than runoff; annual discharge-weighted mean concentrations decline as annual runoff increases. Yields of total nitrogen and most nitrogen fractions bear a relationship to runoff that is nearly indistinguishable from a relationship that was documented previously for minimally disturbed watersheds of the American tropics. Overall, the results suggest strong interlatitudinal convergence of yields and percent fractionation for nitrogen in relation to runoff.

Magill, A.H., Aber, J.D., Berntson, G.M., McDowell, W.H., Nadelhoffer, K.J., Melillo, J.M., and P. Steudler. 2000. Long-term nitrogen additions and nitrogen saturation in two temperate forests. ***Ecosystems*** **3, pp. 238-253.**

Abstract:

This article reports responses of two different forest ecosystems to 9 years (1988–96) of chronic nitrogen (N) additions at the Harvard Forest, Petersham, Massachusetts. Ammonium nitrate (NH_4NO_3) was applied to a pine plantation and a native deciduous broad-leaved (hardwood) forest in six equal monthly doses (May–September) at four rates: control (no fertilizer addition), low N (5 g N m^{-2} y^{-1}), high N (15 g N m^{-2} y^{-1}), and low N + sulfur (5 g N m^{-2} y^{-1} plus 7.4 g S m^{-2} y^{-1}). Measurements were made of net N mineralization, net nitrification, N retention, wood production, foliar N content and litter production, soil C and N content, and concentrations of dissolved organic carbon (DOC) and nitrogen (DON) in soil water. In the pine stand, nitrate losses were measured after the first year of additions (1989) in the high N plot and increased again in 1995 and 1996. The hardwood stand showed no significant increases in nitrate leaching until 1995 (high N only), with further increases in 1996. Overall N retention efficiency (percentage of added N retained) over the 9-year period was 97–100% in the control and low N plots of both stands, 96% in the hardwood high N plot, and 85% in the pine high N plot. Storage in aboveground biomass, fine roots, and soil extractable pools accounted for only 16–32% of the added N retained in the amended plots, suggesting that the one major unmeasured pool, soil organic matter, contains the remaining 68–84%. Short-term redistribution of ^{15}N tracer at natural abundance levels showed similar division between plant and soil pools. Direct measurements of changes in total soil C and N pools were inconclusive due to high variation in both stands. Woody biomass production increased in the hardwood high N plot but was significantly reduced in the pine high N plot, relative to controls. A drought-induced increase in foliar litterfall in the pine stand in 1995 is one possible factor leading to a measured increase in N mineralization, nitrification, and nitrate loss in the pine high N plot in 1996.

Key words: ammonium nitrate; biomass production; foliar chemistry; net mineralization; net nitrification; nitrogen deposition; nitrogen saturation; soil solution chemistry.

McHale, M.R., McDonnell, J.J., Mitchell, M.J., and C.P. Cirmo. 2002. A field-based study of soil water and groundwater nitrate release in an Adirondack forested watershed. Water Resources Research 38(4), pp. 1031-1046.

- Forested watershed
- Adirondack Mountains, New York, USA
- Field Study

Abstract:

Nitrate (NO_3^-) movement was studied using a combination of isotopic, chemical, and hydrometric data within the 135 ha Archer Creek watershed in the Adirondack Mountains of New York from January 1995 to December 1996. This research was conducted to identify sources of stream water NO_3^- and the mechanisms that deliver NO_3^- to the stream to test two hypotheses: (1) Soil water NO_3^- concentrations are highest after dry periods and subsequently lower with each storm. (2) Stream water NO_3^- concentrations are controlled by groundwater during growing season low flows and by soil water during the dormant season and during storms. Antecedent moisture conditions and season had little effect on mean soil water NO_3^- concentrations before storms (range of 1.1–5.1 μmol L^{-1} throughout the study). High soil water NO_3^- concentrations (up to 136 μmol L^{-1}) were found only at the watershed ridge top during the 1996 snowmelt and early summer. Results from isotopic hydrograph separations and chemical end-member mixing analysis showed that soil water and till groundwater dominated stream base flow and storm flow during six monitored storms. Near-stream wetland groundwater and event water contributed little to streamflow during most conditions. Near-stream groundwater contributions to streamflow were significant only during very low base flow (<0.05 mm h^{-1}) during the summer and fall. Highest stream water NO_3^- concentrations coincided with peaks in the till groundwater contribution according to isotopic hydrograph separations using $\delta^{18}O$ and chloride as conservative tracers. A conceptualization of streamflow generation and watershed NO_3^- release is described in which hillslope hollows are the principal zones of soil water and till groundwater mixing in the watershed and till groundwater is the main source of stream water NO_3^- during both base flow and storms.

Annotation:

The authors of this paper present their research as a watershed approach to investigating nitrate release to streams from in forested soils. The watershed approach offers a closer look into the processes controlling nitrate concentrations in stream water, which is the focus of many previous studies. The aim of this paper was to challenge the mechanisms of nitrate transport to streams and lakes that were proposed by Creed et al. (1996) and investigated by Hill et al. (1999). These mechanisms included: 1) nitrate release is controlled by a short-term flushing mechanism such as storm runoff, and 2) nitrate release is controlled by a longer-term draining mechanism such as snowmelt and percolation into groundwater that is subsequently released into the watershed over time. The McHale et al. investigation was centered on a 2-year comprehensive field study along a forest to stream gradient (Archer Creek watershed) in the Adirondack Mountains, New York. Nitrate concentrations were monitored both spatially and temporally in throughfall, meltwater, soil water, groundwater, and stream water throughout the study. The authors considered and monitored most factors influencing controls on the biogeochemical cycling of nitrogen and its hydrologic transport mechanisms, including vegetation, soil type, climate, elevation, season, and storm events.

Results of this study allowed the authors to propose a conceptualization (a model) of nitrate release in the Archer Creek watershed over the course of a year. This seasonal model suggests that during the autumn nitrate export to the stream is low to moderate but increases during storm events; in the winter/spring snowmelt transmittal of nitrate to both groundwater and runoff, combined with influence of storm events cause high levels of nitrate export to the streams; and in the summer nitrate export is low due to low precipitation, and the dilution of groundwater concentrations by low soil water concentrations. McHale et al. identified groundwater has the primary source of nitrate to the Archer Creek watershed throughout the year, confirming the importance of the draining mechanism of transport suggested by Creed et al. (1996). McHale et al. have also identified the importance of soil chemistry and elevation as an influence on the nitrate transport mechanisms. At lower elevations, soil water concentrations indicated that soils acted as nitrate sinks (supporting the findings of Hill et al. (1999)), whereas the soils at higher elevations acted as nitrate sources. In general, this study has shown that comprehensive watershed scale studies are necessary to identify the many natural processes responsible for the transport into, and concentration of nitrate in headwater streams.

Mitchell, M.J., Driscoll, C.T., Inamadar, S., McGee, G.G., Mbila, M.O., and D.J. Raynal. 2003. Nitrogen biogeochemistry in the Adirondack Mountains of New York: hardwood ecosystems and associated surface waters. *Environmental Pollution* 123, pp. 355-364.

Abstract:

Studies on the nitrogen (N) biogeochemistry in Adirondack northern hardwood ecosystems were summarized. Specific focus was placed on results at the Huntington Forest (HFS), Pancake-Hall Creek (PHC), Woods Lake (WL), Ampersand (AMO), Catlin Lake (CLO) and Hennessy Mountain (HM). Nitrogen deposition generally decreased from west to east in the Adirondacks, and there have been no marked temporal changes in N deposition from 1978 through 1998. Second-growth western sites (WL, PHC) had higher soil solution NO_3^- concentrations and fluxes than the HFS site in the central Adirondacks. Of the two old-growth sites (AMO and CLO), AMO had substantially higher NO_3^- concentrations due to the relative dominance of sugar maple that produced litter with high N mineralization and nitrification rates. The importance of vegetation in affecting N losses was also shown for N-fixing alders in wetlands. The Adirondack Manipulation and Modeling Project (AMMP) included separate experimental N additions of $(NH_4)_2SO_4$ at WL, PHC and HFS and HNO_3 at WL and HFS. Patterns of N loss varied with site and form of N addition and most of the N input was retained. For 16 lake/watersheds no consistent changes in NO_3^- concentrations were found from 1982 to 1997. Simulations suggested that marked NO_3^- loss will only be manifested over extended periods. Studies at the Arbutus Watershed provided information on the role of biogeochemical and hydrological factors in affecting the spatial and temporal patterns of NO_3^- concentrations. The heterogeneous topography in the Adirondacks has generated diverse landscape features and patterns of connectivity that are especially important in regulating the temporal and spatial patterns of NO_3^- concentrations in surface waters.

Mitchell, M.J., Driscoll, C.T., Owen, J.S., Schaefer, D. Michener, R. and D.J. Raynal. 2001. Nitrogen biogeochemistry of three hardwood ecosystems in the Adirondack region of New York. *Biogeochemistry* 56(2), pp. 93-133.

Abstract. The biogeochemistry of nitrogen (N) was evaluated for three forest ecosystems [Woods Lake (WL), Pancake-Hall Creek (PHC) and Huntington Forest (HF)] in the Adirondack region of New York, U.S.A. to evaluate the response of a range of N atmospheric inputs and experimental N additions. Bulk N deposition was higher at sites in the west than those in the central and eastern Adirondacks. These higher atmospheric N inputs were reflected in higher bulk throughfall fluxes of N (WL and PHC, 10.1 and 12.0 kg N ha^{-1} yr^{-1}, respectively) in the western Adirondacks than at HF (4.6 kg N ha^{-1} yr^{-1}) in the central Adirondacks. Nitrogen was added to plots as $(NH_4)_2SO_4$ at 14 and 28 kg N ha^{-1} yr^{-1} or as HNO_3 at 14 kg N ha^{-1} yr^{-1}. Litter decomposition rates of *Fagus grandifolia* and *Acer rubrum* were substantially higher at WL and PHC compared to HF but were not affected by experimental N additions. Results using mineral soil bags showed no effects of N addition on N and C concentrations in soil organic matter, but C and N concentration increases were less at WL and PHC compared to HF. Soil solution nitrate (NO_3^-) concentrations at 15-cm depth in the reference plots were higher at PHC than at WL and HF while at 50-cm concentrations were higher at PHC and WL than at HF. The reference plots at the two sites (WL and PHC) with the highest atmospheric inputs of N exhibited lower N retention (53 and 33%, respectively) than HF (68%) in reference plots. The greatest increase in NO_3^- loss in response to the experimental treatments occurred at HF where the HNO_3 additions resulted in the highest NO_3^- concentrations and lowest N retentions. In contrast, at WL and PHC increases in soil water NO_3^- were not evident in response to experimental N additions. The results suggest that the two sites (WL and PHC) in the western Adirondacks did not respond to additional N inputs although they have experienced elevated atmospheric N inputs and higher N drainage losses in reference plots than the HF site in the central Adirondacks. Some of these differences in site response may have also been a function of stand age of WL and PHC that were younger (24 and 33 years, respectively) than the HF (age $\sim$ 70). Highest NO_3^- fluxes in the reference plots across the sites corresponded to higher $\delta^{15}N$ values in soil and plants. An experimental addition experiment at PHC found that the forest floor and the mineral soil were the largest sinks for experimentally added N.

Nadelhoffer, K., Downs, M., Fry, B., Magill A., and J. Aber. 1999. Controls on N retention and exports in a forested watershed. *Environmental Monitoring and Assessment* 55, pp. 187-210.

Abstract. We conducted a ^{15}N-tracer study in a fertilized, forested catchment at the Bear Brook Watersheds in Maine (BBWM), USA, in order to characterize N cycling processes, identify sinks for ammonium-N additions, and determine the contribution of the experimental ammonium additions to nitrate exports from the treated catchment. Distributions of ^{15}N in plant tissues, soils, precipitation and streamwater collected before adding tracers showed that nitrate-N (the dominant form of inorganic N deposition at the site) inputs under ambient conditions were depleted in ^{15}N relative to plants and that soil was enriched in ^{15}N relative to plants. The ^{15}N content of streamwater nitrate was within the range of ^{15}N contents in natural plant tissues, suggesting that nitrate deposited from the atmosphere is reduced and assimilated into soil and plant N pools before being leached as nitrate from the catchment. Variations in ^{15}N natural abundances also suggested that most N uptake by trees is from the forest floor and that nitrification occurs in soils at this catchment under ambient conditions. Changes in ^{15}N contents of plant tissues, soils and streamwater after adding a ^{15}N tracer to the ammonium sulfate fertilizer applied to the treated catchment showed that soils were the dominant sink for the labeled ammonium. Surface soils (Oea horizon plus any underlying mineral soil to 5cm depth) assimilated 19 to 31 percent of the 42 kg ha^{-1} of ^{15}N-labelled ammonium-N during the tracer study. Aboveground biomass assimilated 8 to 17 percent of the labeled ammonium-N additions. Of the three forest types on the catchment, the soil:biomass assimilation ratio of labeled-N was highest in the spruce forest, intermediate in the beech-dominated hardwood forest and lowest in the mixed hardwood-spruce forest. Although ammonium sulfate additions led to increases in streamwater nitrate, only 2 of the 13 kg ha^{-1} of nitrate-N exported from the catchment during the 2 years of tracer additions was derived from the 42 kg ha^{-1} of labeled ammonium-N additions.

Nelson W.M., Gold, Arthur J., and Peter M. Groffman. 1995. Spatial and temporal variation in groundwater nitrate removal in a riparian forest. *Journal of Environmental Quality* 24, pp. 691-699.

Abstract:

We quantified nitrate (NO_3^-) removal rates from groundwater in a red maple *(Acer rubrum* L.) riparian forest subjected to NOj- dosing. The site was in Southern New England on soils classified as sandy mixed mesic Haplaquept soils and contained somewhat poorly (SPD) and poorly drained (PD) soils. The specific objectives were to examine groundwater NO£ removal rates within a riparian forest with respect to: (i) soil drainage class; (il) depth below water table; and (ili) time of year. We created 16 experimental dosing/monitoring stations at two depths along three soil drainage class transects (SPD, SPD/ PD, PD). We added solution containing NO~- and Br- continuously for II mo to a dosing well at each station. Groundwater was monitored at sampling wells 0.6 m downgradient of the dosing well. Nitrate removal rates were determined by coupling changes in the NO~-/Brratio wth groundwater flux estimates from each experimental station.Although located just 20 m downgradient, the PD transects had substantially higher NO£ removal rates and lower dissolved oxygen than the SPD transects. Both the SPD/PD and PD transects had considerable NO~" -N removal capacity throughout the upper 1.5 m oftbe groundwater (16-46 lag kg-~ d-l). Rates were not significantly influenced by temperature. The scale of variation in removal rates suggests that high resolution soil and groundwater maps may be needed when riparian forests are to be used for water quality management.

Perakis, S.S., Compton J.E., and L.O. Hedin. 2005. Nitrogen retention across a gradient of ^{15}N additions to an unpolluted temperate forest soil in Chile. *Ecology* 86(1), pp. 96-105.

- Coastal montaine old-growth forest, mixed evergreens
- Parque Nacional Chiloe, Chile (42 30S, 74 03W)
- Field Study
- Measured nitrogen species under various nitrogen addition regimes

Abstract. Accelerated nitrogen (N) inputs can drive nonlinear changes in N cycling, retention, and loss in forest ecosystems. Nitrogen processing in soils is critical to understanding these changes, since soils typically are the largest N sink in forests. To elucidate soil mechanisms that underlie shifts in N cycling across a wide gradient of N supply, we added $^{15}NH_4{}^{15}NO_3$ at nine treatment levels ranging in geometric sequence from 0.2 kg to 640 kg $N \cdot ha^{-1} \cdot yr^{-1}$ to an unpolluted old-growth temperate forest in southern Chile. We recovered roughly half of ^{15}N tracers in 0–25 cm of soil, primarily in the surface 10 cm. Low to moderate rates of N supply failed to stimulate N leaching, which suggests that most unrecovered ^{15}N was transferred from soils to unmeasured sinks above ground. However, soil solution losses of nitrate increased sharply at inputs >160 kg $N \cdot ha^{-1} \cdot yr^{-1}$, corresponding to a threshold of elevated soil N availability and declining ^{15}N retention in soil. Soil organic matter (<5.6 mm) dominated tracer retention at low rates of N input, but coarse roots and particulate organic matter became increasingly important at higher N supply. Coarse roots and particulate organic matter together accounted for 38% of recovered ^{15}N in soils at the highest N inputs and may explain a substantial fraction of the "missing N" often reported in studies of fates of N inputs to forests.

Contrary to expectations, N additions did not stimulate gross N cycling, potential nitrification, or ammonium oxidizer populations. Our results indicate that the nonlinearity in N retention and loss resulted directly from excessive N supply relative to sinks, independent of plant–soil–microbial feedbacks. However, N additions did induce a sharp decrease in microbial biomass C:N that is predicted by N saturation theory, and which could increase long-term N storage in soil organic matter by lowering the critical C:N ratio for net N mineralization. All measured sinks accumulated ^{15}N tracers across the full gradient of N supply, suggesting that short-term nonlinearity in N retention resulted from saturation of uptake kinetics, not uptake capacity, in plant, soil, and microbial pools.

Annotation:

This study examined soil mechanisms that underlie shifts in N cycling across a wide gradient of N supply by adding $^{15}NH_4$ $^{15}NO_3$ at nine treatment levels ranging from 0.001 to 4.6 mol N m^{-2} yr^{-1} to an unpolluted old-growth forest. Most of the added ^{15}N was found in the upper 10 cm of soil. Low to moderate N addition didn't stimulate N leaching, suggesting most unrecovered ^{15}N was transferred from soils to unmeasured sinks aboveground (leaf litter samples were lost in transit and not measured; above-ground biomass and ^{15}N content wasn't measured). Soil organic matter dominated tracer retention at low rates of N input, but coarse roots and POM became increasingly important at higher N supply. Coarse roots and particulate OM together accounted for 38% of recovered ^{15}N in soils at the highest N input and may explain a substantial fraction of the missing N often reported in studies of fates of N input to forests.

N additions did not stimulate gross N cycling, potential nitrification, or ammonium oxidizer populations. Nonlinearity in N retention and loss resulted directly from excessive N supply relative to sinks, independent of plant-soil-microbe feedbacks. However N addition did induce a sharp decrease in long-term N storage in soil OM by lowering the critical C:N ratio for net N mineralization.

Rotkin-Ellman, M., Addy, K., Gold, A.J., and P.M. Groffman. 2004. Tree species, root decomposition and subsurface denitrification potential in riparian wetlands. *Plant and Soil* 263, pp. 335-344.

Abstract:

Patches of organic matter have been found to be important "hotspots" of denitrification in both surface and subsurface soils, but the factors controlling the formation and maintenance of these patches are not well established. We compared the concentration of patches of organic matter and root biomass in the subsurface (saturated zone) beneath poorly drained riparian wetland soils at four sites in Rhode Island, U.S.A. - two dominated by red maple *(Acer rubrum)* and two dominated by white pine *(Pinus strobus*). Denitrification enzyme activity (DEA) and carbon (C) content of patch material were compared between sites and between patches with different visual characteristics. Root decomposition was measured in an 8-week ex-situ incubation experiment that compared the effects of water content, root species, and soil matrix origin on CO2 evolution. We observed significantly greater concentrations of patches at 55 cm at one red maple site than all other sites. DEA and percent C in patches was generally higher in patches than matrix soil and did not vary between sites or by patch type. White pine roots decomposed at a faster rate than red maple roots under unsaturated conditions. Our results suggest that faster root decomposition could result in lower concentrations of patches of organic material in subsurface soils at sites dominated by white pine. Tree species composition and root decomposition may play a significant role in the formation of patches and the creation and maintenance of groundwater denitrification hotspots in the subsurface of riparian wetlands.

Seely B., Lajtha, K., and G.D. Salvucci. 1998. Transformation and retention of nitrogen in a coastal forest ecosystem. *Biogeochemistry* 42, pp. 325-343.

- Forested coastal watershed with mixed land use
- Waquoit Bay watershed, Cape Cod Massachusetts
- Field Study
- Measured NH_4-N, NO_3-N, PO_4, total persulfate N, and bromide (as reference ion) in precipitation, throughfall, and ground water at three sites based on soil texture: fine sand, loamy sand and coarse sand.

Abstract not available electronically

Annotation:

Transformations and fluxes of N were monitored in three forested sites along a gradient of soil texture. Nitrate and DON showed a substantial increase in throughfall relative to bulk precipitation. For nitrate, this was likely due to wash-off of nitrate aerosols and particulates which had previously been deposited on vegetation surfaces via dry deposition. For DON, the increase during passage through the canopy was likely due to the leaching of organic N from leaf and stem tissues. Some of the DON may have originated as atmospherically deposited inorganic N which was subsequently converted to DON by microbial activity on canopy surfaces.

Total N leaching losses to ground water were 0.004 mol m^{-2} yr^{-1} in the loamy sand site and 0.011 mol m^{-2} yr^{-1} in the fine sand site. Leaching loss to ground water was not measured in the coarse sand site because of the prohibitive depth of the water table, but total N leaching loss to 1 m depth in the mineral soil was 0.028 mol m^{-2} yr^{-1}. DON accounted for most of the leaching losses below the rooting zone (77-89%) and through the soil profile to ground water (60-80%). This is in contrast to certain other studies that indicate NO_3^- leaching to be the dominant vector of N loss to streams and ground water. Differences in DON retention capacity of the mineral soil in the sites along the soil texture gradient were most likely related to changes in mineral soil particle surface area and percolation rates associated with soil texture. Forests of the watershed functioned as a sink for inorganic N deposited on the surface of the watershed in wet and dry deposition but a source of dissolved organic N to ground water and adjoining coastal ecosystems.

2.0 EMERGENT SHRUB-SCRUB

Hurd, T.M. and D.J. Raynal. 2004. Comparison of nitrogen solute concentrations within alder (*Alnus incana* ssp *rugosa*) and non-alder dominated wetlands. *Hydrological Processes* 18, pp. 2681-2694.

Abstract:

This study examined differences in nitrogen solutes and groundwater flow patterns between a riparian wetland dominated by the N_2-fixing shrub, *Alnus incana* ssp. *rugosa*, and an upstream coniferous forested riparian wetland along a stream of the Adirondack Mountains, where some surface waters are susceptible to nitrogen excess. Channel water NO_3^- was up to 16 µmol l^{-1} greater in the alder reach, with peaks following maxima in groundwater dissolved inorganic nitrogen (DIN). NO_3^- at 25 cm depth was 30 µmol greater in the alder than in the conifer reach in April, and 24 µmol l^{-1} greater than channel water and 30 µmol l^{-1} greater than that of 125 cm groundwater in June. Dissolved organic nitrogen and NH_4^+ concentrations increased between 25 and 75 cm depths in both wetlands during the growing season. Inorganic nitrogen increased between the hillslope and stream in both wetlands, with the greatest increases in the alder reach during the dormant season. Greatest subsurface DIN (120 µmol l^{-1}) occurred at 75 cm in the alder reach, within 1 m of the stream, between November (120 µmol l^{-1} NH_4^+) and a January thaw (60 µmol l^{-1} each of NH_4^+ and NO_3^-). Concentrations of deeper groundwater at 125 cm during this period were lower (10–30 µmol l^{-1}). Lateral flow from the stream channel occurred in the alder reach during the dormant season, and channel water contribution to groundwater was correlated strongly to NO_3^- at 25 cm. These results indicate that nitrification is stimulated in the presence of alders and oxidized exchange flow, producing NO_3^- that may contribute to elevated channel water NO_3^- during periods of peak flow.

Hurd, T.M., Raynal, D.J., and C.R. Schwintzer. 2001. Symbiotic N_2 fixation of *Alnus incanassp. Rugosain* shrub wetlands of the Adirondack Mountains, New York, USA. *Oecologia* 126, pp. 94-103.

- Shrub-scrub wetland
- Adirondack Mountains
- Field study
- Reports above and below-ground Alder biomass, nitrogen species, natural 15-N abundance (for nitrogen fixation estimates)

Abstract:

Surface waters in forested watersheds in the Adirondack Mountains and northern New York State are susceptible to nitrogen (N) saturation. Atmospheric deposition of N to watersheds in this region has been measured but the extent of internal N inputs from symbiotic N_2 fixation in alder-dominated wetlands is not known. We estimated N_2 fixation by speckled alder in these wetlands by the ^{15}N natural abundance method and by acetylene reduction using a flow-through system. Foliar N derived from fixation (%N_{dfa}) was estimated for five wetlands. The $\delta^{15}N$ of speckled alder foliage from four of the five sites did not differ significantly ($P \leq 0.05$) from that of nodulated speckled alders grown in N-free water culture (–1.2±0.1‰). Estimates from the ^{15}N natural abundance method indicated that alders at these sites derive 85–100% of their foliar N from N_2 fixation. At one of the sites, we also measured biomass and N content and estimated that the alder foliage contained 43 kg N ha^{-1} of fixed N in 1997. This estimate was based on a foliar N content of 55.4±7 kg N ha^{-1} (mean±SE), 86±4%N_{dfa}, and an assumption that 10% of foliar N was derived from reserves in woody tissues. At this site, we further estimated via acetylene reduction that 37±10 kg N ha^{-1} was fixed by speckled alders in 1998. This estimate used the theoretical 4:1 C_2H_2 reduction to N_2 fixation ratio and assumed no night-time fixation late in the season. Nitrogen inputs in wet and dry deposition at this site are approximately 8 kg N ha^{-1} $year^{-1}$. We conclude that speckled alder in wetlands of northern New York State relies heavily on N_2 fixation to meet N demands, and symbiotic N_2 fixation in speckled alders adds substantial amounts of N to alder-dominated wetlands in the Adirondack Mountains. These additions may be important for watershed N budgets, where alder-dominated wetlands occupy a large proportion of watershed area.

Annotation:

Study provides field estimates of symbiotic N_2 fixation in alder dominated wetlands and examined the contribution of nitrogen fixation to nitrogen budget. Found that Alders obtain large amounts of N from fixation, even in the Adirondacks, an area of high and increasing atmospheric N deposition.

Implications:

- Alders continue to fix nitrogen even when ambient levels are relatively high
- Nitrogen fixation by these shrubs can contribute a substantial amount of N to the total budget
- Studies of wetland N retention should account for this internal N source
- Wetlands designed for nitrogen retention should not use Alder; existing Alder-dominated wetlands would not be prime candidates for nitrogen attenuation efforts

Hurd, T.M., Raynal, D.J. and C.R. Schwintzer. 2001. Symbiotic fixation of Alnus incana ssp. rugosa in shrub wetlands of the Adirondack mountains, New York, USA. *Oecologia* 126, pp. 94-103.

Abstract Surface waters in forested watersheds in the Adirondack Mountains and northern New York State are susceptible to nitrogen (N) saturation. Atmospheric deposition of N to watersheds in this region has been measured but the extent of internal N inputs from symbiotic N_2 fixation in alder-dominated wetlands is not known. We estimated N_2 fixation by speckled alder in these wetlands by the ^{15}N natural abundance method and by acetylene reduction using a flow-through system. Foliar N derived from fixation ($\%N_{dfa}$) was estimated for five wetlands. The $\delta^{15}N$ of speckled alder foliage from four of the five sites did not differ significantly ($P \leq 0.05$) from that of nodulated speckled alders grown in N-free water culture (–1.2±0.1‰). Estimates from the ^{15}N natural abundance method indicated that alders at these sites derive 85–100% of their foliar N from N_2 fixation. At one of the sites, we also measured biomass and N content and estimated that the alder foliage contained 43 kg N ha^{-1} of fixed N in 1997. This estimate was based on a foliar N content of 55.4±7 kg N ha^{-1} (mean±SE), 86±4%N_{dfa}, and an assumption that 10% of foliar N was derived from reserves in woody tissues. At this site, we further estimated via acetylene reduction that 37±10 kg N ha^{-1} was fixed by speckled alders in 1998. This estimate used the theoretical 4:1 C_2H_2 reduction to N_2 fixation ratio and assumed no night-time fixation late in the season. Nitrogen inputs in wet and dry deposition at this site are approximately 8 kg N ha^{-1} $year^{-1}$. We conclude that speckled alder in wetlands of northern New York State relies heavily on N_2 fixation to meet N demands, and symbiotic N_2 fixation in speckled alders adds substantial amounts of N to alder-dominated wetlands in the Adirondack Mountains. These additions may be important for watershed N budgets, where alder-dominated wetlands occupy a large proportion of watershed area.

Keywords Actinorhizal plants · *Alnus* · Nitrogen fixation · Adirondack Mountains

Introduction

The actinorhizal shrub *Alnus incana* ssp. *rugosa* (speckled alder) forms a root nodule symbiosis with N_2-fixing actinomycetes of the genus *Frankia*, and dominates some shrub and riparian wetlands of northeast North America (Furlow 1979). Speckled alder is the dominant species of the second largest wetland covertype [Scrub-Shrub 1 (Cowardin et al. 1979)] in the Adirondack Mountains (Roy et al. 1996), a region with surface waters that are susceptible to N saturation or excess N (Stoddard 1994). Nevertheless, N_2 fixation in speckled alder has not been quantified in Adirondack wetlands.

A wide range of N_2 fixation has been reported for

Hurd, T.M., Gokkaya, K., Kiernan, B.D., and D.J. Raynal. 2005. Nitrogen sources in Adirondack wetlands dominated by nitrogen-fixing shrubs. *Wetlands* 25(1), pp. 192–199.

Abstract:

In the Adirondack region of northern New York, USA, *Alnus incana* ssp. *rugosa* and *Myrica gale* often dominate wetland shrub communities and fix nitrogen in symbiosis with actinomycetes of the genus *Frankia*. The objective of this study was to examine the contribution of these shrubs to the N economies of whole wetlands in the Adirondacks where N has been considered a potential pollutant and contributor to low acid-neutralizing capacity, and where N deposition may reduce rates of nitrogen fixation in actinorhizal plants. Nitrogen chemistry of plant foliage was examined, and density and foliar biomass of nitrogen fixing shrubs were estimated in plots or belt transects in six shrub wetlands near atmospheric deposition monitoring stations in order to estimate the fraction of N derived from fixation in *A. incana* ssp. *rugosa* and *M. gale* tissues. Lake-inlet-wetlands were dominated by alder that derives $85% foliar N from fixation, but *M. gale* was most abundant in lake outlet wetlands and seemed to rely less on fixed N, although results for *Myrica* were more uncertain. Substantial N is therefore added to lake inlet systems dominated by alder (7–18 kg ha21 yr21), while N fixed from *M. gale* does not appear to exceed 3 kg ha21 yr21, except in localized patches at smaller spatial scales. Similarity in d15N between non-fixing field shrubs and reference values for fixed N at some sites suggests that fixed N is being recycled in the plant community. Wet atmospheric N deposition is 3–6 kg ha21 yr21 and does not decrease N fixation substantially in alder. Overall, shrubs in wetlands dominated by these actinorhizal N_2—fixing plants are not taking up substantial quantities of anthropogenic N, suggesting that nitrogen is processed microbially or transferred along with some fixed N to downstream ecosystems.

Kao, J.T., Titus, J.E., and W-X. Zhu. 2003. Differential nitrogen and phosphorus retention by five wetland plant species. *Wetlands* 23(4), pp. 979-987.

Abstract:

Riparian wetlands have a demonstrated ability to filter and control nitrogen (N) and phosphorus (P) movement into streams and other bodies of water; few studies, however, have examined the roles that individual plant species serve in sequestering N and P pollutants. We evaluated the potential for growth and consequent N and P accumulation by five species of wetland perennials. We planted blocks consisting of 900-cm2 plots of each species at 11 sites within a riparian wetland that receives large inputs of agricultural runoff. Plant shoots and roots were collected at the time of peak standing crop to determine net accumulation of biomass, N, and P for one growing season. A portion of the plant shoots was placed in decomposition litterbags in the field to determine biomass, N, and P losses for 60, 120, and 150 days. Of the five species, bur reed (Sparganium americanum) had the greatest aboveground accumulation of N and P but had the lowest belowground accumulation values. In contrast, woolgrass (Scirpus cyperinus) had the lowest aboveground values for N and P accumulation but had the highest belowground value for P. Soft rush (Juncus effusus) and reed canary grass (Phalaris arundinacea) showed high values for both aboveground and belowground N and P accumulation, while blue joint grass (Calamagrostis canadensis) showed low values for aboveground N and P. The five species also showed wide variations in the retention of N and P in decomposing shoots. Juncus effusus had the highest percentages of N and P remaining in litter after five months (87% N and 69% P), while P. arundinacea retained only 28% N and 18% P. Sparganium americanum had high retention rate for N in litter (74% N) but showed low P retention values (35%). Scirpus cyperinus and C. canadensis also showed high retention rates of litter N but lower values for P retention. Our study suggests that species show differential accumulation and release of N and P and may influence the overall potential of a wetland to retain agricultural nutrients.

Kiernan, B.D., Hurd, T.M., and D.J. Raynal. 2003. Abundance of Alnus incana ssp. rugosa in Adirondack Mountain shrub wetlands and its influence on inorganic nitrogen. *Environmental Pollution* 123, pp. 347–354

Abstract:

The purpose of this research was to determine the abundance of the nitrogen-fixing shrub, Alnus incana ssp. rugosa (speckled alder), in shrub wetlands of the Adirondack Mountain region of New York State and to determine whether its abundance affects the concentration or accumulation of inorganic nitrogen in wetland substrates. Alder/willow wetlands are the second most common wetland type in the Adirondack region. The Adirondack Park Agency's digital GIS database of wetland types was used to determine the areal extent of alder/willow wetlands in the Adirondacks. Randomly selected wetlands were sampled to determine the size and abundance of alder. Alder densities averaged 7000 stems ha^{1} and alder was present in 75% of the wetlands. As an indication of short-term accumulation of NO3^{+} in wetland substrates, ion exchange resins were used to sample ground water in high and NH4 and low alder density wetlands as well as from wetlands lacking alder and dominated byconifers. Additionally, NO3 and NH4 concentrations in ground water samples were measured. NH4 accumulation levels from exchange resins were low for all wetland types while groundwater NH4 concentration was highest in the low-density alder sites. Wetlands with high alder density had approximately six times higher NO3 concentrations in wetlands of accumulation than other wetlands. Substrate groundwater NO3high-densityalder exceeded by three times levels in low or no alder wetlands, showing the importance of alder to local N budgets. To assess the recovery of shrub wetlands from acidification, future studies should determine the fate of fixed N in wetland systems.

Moore, JRJ, P.A. Keddy, CL Gaudet, and IC Wisheu. 1989. Conservation of wetlands: Do infertile wetlands deserve a higher priority? Biological Conservation 47:203-217.

- Emergent shrub-scrub wetland
- Canada
- Field Study
- Presents data on nitrate, total phosphorus, magnesium, and potassium, plant species composition, species richness, and rare species occurrence

Abstract:

In this study we evaluate whether infertile wetlands had higher conservation value than fertile wetlands based on three criteria commonly used in ecological site evaluations: species richness, number of rare species and species composition. The data consisted of species composition in $n = 401$ $0{\cdot}25\ m^2$ quadrats from a wide range of wetland types in eastern Canada.

Infertile wetlands had higher species richness and many more rare species than did fertile wetlands. Further, infertile wetlands had a greater range of vegetation types than did fertile wetlands. It is also probable that infertile wetlands are more sensitive to human disturbances. These results indicate that infertile wetlands are more desirable for conservation than presently accounted for in wetland evaluation systems. In addition, because of greater variation in vegetation types, relatively more ecological reserves are needed to adequately represent the variation in infertile wetlands.

Annotation:

This study showed that wetlands with lower nutrient status and less plant biomass had higher species richness and more rare species than wetland with more biomass and higher nutrient levels. Because of this the authors suggest conservation efforts should focus on low nutrient/low productivity wetlands. Further, the authors suggest eutrophication of wetlands is likely to reduce species richness and convert unique vegetation types to those more commonly observed. They note many rare species which are usually of small stature will be competitively eliminated by large, rapidly growing species such as *Typha* which are capable of surviving in more fertile areas. They note *Typha* is a large clonal perennial that competitively eliminates the smaller less aggressive infertile wetland species. The implication for this study is that increased nutrient loading to wetlands via diversion of nutrient-rich water could change species composition and reduce rare species abundance.

3.0 RIPARIAN ZONES

Addy, K., Kellogg, D.Q., Gold, A.J., Groffman, P.M., Ferendo, G., and C. Sawyer. 2002. In situ push–pull method to determine ground water denitrification in riparian zones. *Journal of Environmental Quality* 31, pp. 1017–1024.

- Riparian zones – one fresh and one brackish
- Rhode Island, USA
- Field experiment
- Reports groundwater temperature, DO, pH, DOC, NO_3^--N, Br^-, salinity, soil texture class

Abstract:

To quantify ground water denitrification in discrete locations of riparian aquifers, we modified and evaluated an in situ method based on conservative tracers and 15N-enriched nitrate. Ground water was "pushed" (i.e., injected) into a mini-piezometer and then "pulled" (i.e., extracted) from the same mini-piezometer after an incubation. This push–pull method was applied in replicate mini-piezometers at two Rhode Island riparian sites, one fresh water and one brackish water. Conservative tracer pretests were conducted to determine incubation periods, ranging from 5 to 120 h, to optimize recovery of introduced plumes. For nitrate push–pull tests, we used two conservative tracers, sulfur hexafluoride and bromide, to provide insight into plume recovery. The two conservative tracers behaved similarly. The dosing solutions were amended with 15N-enriched nitrate that enabled us to quantify the mass of denitrification gases generated during the incubation period. The in situ push–pull method detected substantial denitrification rates at a site where we had previously observed high denitrification rates. At our brackish site, we found high rates of ground water denitrification in marsh locations and minimal denitrification in soils fringing the marsh. The push–pull method can provide useful insights into spatial and temporal patterns of denitrification in riparian zones. The method is robust and results are not seriously affected by dilution or degassing from ground water to soil air. In conjunction with measurements of ground water flow paths, this method holds promise for evaluating the influence of site and management factors on the ground water nitrate removal capacity of riparian zones.

Annotation:

This study describes an innovative method for measuring in-situ denitrification rates, and examines denitrification in two riparian areas – one fresh and one brackish. In-situ enitrification rates were found to be significantly higher than those measured at the same site using mesocosms (Addy 1999, summarized above). The difference was attributed to seasonality (this study was done in November; Addy 1999 was done in June), as well as possible labile carbon limitations in the Addy (1999) study. Results also showed significantly higher denitrification rates in the brackish area (mean = 123.2 um N $kg^{-1}d^{-1}$) than in fringe sites (mean = 2.1 ug N $kg^{-1}d^{-1}$). These results were noted to be in accordance with the difference in ground water denitrification rates expected for these areas. The implication for this study is that brackish marsh areas may provide better nitrogen removal than the freshwater areas surrounding them.

Burns, DA. 1998. Retention of NO_3- in an upland stream environment: a mass balance approach. *Biogeochemistry* 40, pp. 73-96.

Abstract. Models of the effects of atmospheric N deposition in forested watersheds have not adequately accounted for the effects of aquatic and near-stream processes on the concentrations and loads of NO_3^- in surface waters. This study compared the relative effects of aquatic and near-stream processes with those from the terrestrial ecosystem on the retention and transport of NO_3^- in two contrasting stream reaches of the Neversink River, a forested watershed in the Catskill Mountains of New York that receives among the highest load of atmospheric N deposition in the northeastern United States. Stream water samples were collected every two hours and ground-water and tributary samples were collected daily at base flow conditions during four 48-hour periods from April to October 1992, and NO_3^- mass balances were calculated for each site. Results indicated diurnal variations in stream NO_3^- concentrations in both reaches during all four sampling periods; this is consistent with uptake of NO_3^- by photoautotrophs during daylight hours. Mass-balance results revealed significant stream reach losses of NO_3^- at both sites during all sampling periods. The diurnal variations in NO_3^- concentrations and the retention of NO_3^- relative to terrestrial contributions to the stream reaches were greater downstream than upstream because physical factors such as the head gradients of inflowing ground water and the organic matter content of sediment are more favorable to uptake and denitrification downstream. The mass retention of NO_3^- increased as the mean 48-hr stream discharge increased at each site, indicating that the responsible processes are dependent on NO_3^- supply. Low stream temperatures during the April sampling period, however, probably reduced the rate of retention processes, resulting in smaller losses of NO_3^- than predicted from stream discharge alone. Water samples collected from the stream, the hyporheic zone, and the alluvial ground water at sites in both reaches indicated that the net effect of hyporheic processes on downstream NO_3^- transport ranged from conservative mixing to complete removal by denitrification. The relative effects of biological uptake and denitrification as retention mechanisms could not be quantified, but the results indicate that both processes are significant. These results generally confirm that aquatic and near-stream processes cause significant losses of NO_3^- in the Neversink River, and that the losses by these processes at downstream locations can exceed the NO_3^- contributions to the stream from the terrestrial environment during summer and fall base-flow conditions. Failure to consider these aquatic and near-stream processes in models of watershed response to atmospheric N deposition could result in underestimates of the amount of NO_3^- leaching from forested ecosystems and to an inability to unequivocally relate geographic differences in NO_3^- concentrations of stream waters to corresponding differences in terrestrial processes.

Casey, R.E. and S.J. Klaine. 2001. Nutrient attenuation by a riparian wetland during natural and artificial runoff event. *Journal of Environmental Quality* 30, pp. 1720-1731.

- Riparian freshwater wetland
- Cheraw State Park Golf Course, Sandhills physiographic region, South Carolina
- Field study
- Data on NO_3, PO_4 at inlet and outlet areas

Abstract:

Due to chronic nutrient enrichment of surface water, wetlands adjacent to land managed with fertilizer have been studied to determine their role in nutrient dynamics. We sampled golf course runoff and determined the loads of NO_3 and PO_4 transported during storms and the attenuation of those loads when runoff passed through a riparian wetland. All sampled storm events contained NO_3 (2 to 1470 g NO_3–N per event) and PO_4 (1 to 4156 g PO_4–P per event). Extensive nutrient attenuation occurred when water passed through the riparian wetland. In 11 events, NO_3 and PO_4 attenuation averaged 80 and 74%, respectively. In subsequent experiments, we created a stream of water flowing into the wetland and amended it with NO_3, PO_4 and Br^-, creating an artificial runoff event. The experiments were conducted using conditions similar to those of natural runoff events. We observed rapid and complete attenuation of PO_4 immediately after runoff water infiltrated into the wetland subsurface. No PO_4 was observed in discharge from the wetland. Nitrate attenuation occurred following a lag phase of several hours that was probably due to reactivation of denitrifying enzymes. Nitrate attenuation was initially less than 60% but increased to 100% in all experiments. We observed extensive dilution of runoff water in the wetland subsurface indicating mixing with pre-event ground water in the wetland. The results indicated that intermittent inputs of NO_3 and PO_4 could be successfully attenuated in the wetland on the time scale of natural storm events.

Annotation:

This study reports on measured loads of nitrate and phosphate in turfgrass runoff and estimates the efficiency of the wetland for removing nutrients from storm-generated runoff. It also reports on artificial runoff events and quantified nutrient removal rates. Significant nutrient retention occurred during these events, suggesting the wetland is effective in removing nutrients generated during storms. When the runoff rate was excessive in artificial storm events, limited seepage into organic soils, and reduced contact with these resulted in less efficient removal of nitrogen.

Implications:

- Riparian wetlands may be effective at removing nitrogen from stormwater, even without constant exposure to high nitrogen levels

Cirmo, C.P. and J.J. McDonnell. 1997. Linking the hydrologic and biogeochemical controls of nitrogen transport in near-stream zones of temperate-forested catchments: a review. Journal of Hydrology 199, pp. 88-120.

- Riparian zone, forested streams
- Various locations in the eastern United States and Europe
- Literature review

Abstract:

We review the status of research concerning the links between hydrologic towpaths and the biogeochemical environment controlling Nitrogen cycling and transport in near-stream saturated zones, centering on stream environments of the northern, temperate-forested zone. N retention, transformation and mobilization occur in streamside wetlands, floodplains, riparian zones, seepage faces, and the hyporheic zone. These areas are the focal point in non-point source loading of N to stream channels. They also represent areas where rapid changes in water-table and hydrologic towpaths occur during rainfall-runoff events. It is the combination of an abrupt change in biogeochemical environment, encountering a hydrologic boundary (the terrestrial/aquatic interface or ecotone), that make the near-stream/saturated zone critical for elucidating controls of N transport and transformation. We review published studies concerning the hydrologic controls of N transport in near-stream zones, and subsequently present several geomorphic and hydrodynamic scenarios relating N biogeochemistry and its response to hydrologic events (of both varying magnitude and seasons). It is at the critical junction between temporal and spatial conditions affecting N cycling in the near-stream zone, that research priorities must now be focused.

Annotation:

This review provides in depth descriptions of hydrologic flowpaths and processes of nitrogen transformation in forested watershed, and specifically near the riparian transition zone. This review contains much of the same overview information that is found in the background sections of other papers, or in reviews from other types of ecosystems, but is useful due to its focus on terrestrial systems. In terrestrial ecosystems and coastal marine ecosystems many of the same controlling factors over nitrogen cycling exist. A primary controlling factor over whether saturated near-stream zones are sources or sinks of nitrogen is the availability of carbon for denitrifiers. Other controlling factors include the availability of phosphorous, oxygen, acidity, and temperature. Denitrification is considered an important mode of nitrogen attenuation in terrestrial catchments with excess nitrate runoff. Upland soils typically exhibit lower denitrification rates than lower elevation or riparian soils. Groundwater flow and transport of nitrogen may be significant, and can vary from overland (and stream) flow in chemical properties and on a temporal scale. Towards the end of the review the authors present a seasonal hydrological and biogeochemical model of nitrogen cycling and transport in a riparian zone. This general model, modified from Pinay and DeCamps (1988) (Figure 8), is useful in that it provides a visual flow chart of the complex seasonal cycle described in the text. Following this model are two others, depicted in Figures 9 and 10, which also generalize nitrate and ammonium concentrations over the course of the seasons in a near-stream zone. These three figures are presented prior to the conclusion of the review, and highlight the objective of the authors to address the importance of the dynamic near-stream/riparian zone as an ecological zone of transition at a surface and groundwater interface, which impacts the biogeochemical cycling of nitrogen.

Forshay, K.J. and E.H. Stanley. 2005. Rapid nitrate loss and denitrification in a temperate river floodplain. *Biogeochemistry* 75, pp. 43-64

- Riverine floodplain
- Leopold Memorial Reserve on the Wisconsin River, a 7th order tributary on the Mississippi River
- Field experiment
- Measured total dissolved nitrogen (TDN), NO_3-N, NH_4^+-N, and dissolved organic N (DON)

Abstract:

Nitrogen (N) pollution is a problem in many large temperate zone rivers, and N retention in river channels is often small in these systems. To determine the potential for floodplains to act as N sinks during overbank flooding, we combined monitoring, denitrification assays, and experimental nitrate (NO3-N) additions to determine how the amount and form of N changed during flooding and the processes responsible for these changes in the Wisconsin River floodplain (USA). Spring flooding increased N concentrations in the floodplain to levels equal to the river. As discharge declined and connectivity between the river and floodplain was disrupted, total dissolved N decreased over 75% from 1.41 mg l^{1}, equivalent to source water in the Wisconsin River on 14 April 2001, to 0.34 mg l^{1} on 22 April 2001. Simultaneously NO3-N was attenuated almost 100% from 1.09 to <0.002 mg l^{1}. Unamended sediment denitrification rates were moderate (0– 483 lgm^{2} h^{1}) and seasonally variable, and activity was limited by the availability of NO3-N on all dates. Two experimental NO3-N pulse additions to floodplain water bodies confirmed rapid NO3-N depletion. Over 80% of the observed NO3-N decline was caused by hydrologic export for addition #1 but only 22% in addition #2. During the second addition, a significant fraction (>60%) of NO3-N mass loss was not attributable to hydrologic losses or conversion to other forms of N, suggesting that denitrification was likely responsible for most of the NO3-N disappearance. Floodplain capacity to decrease the dominant fraction of river borne N within days of inundation demonstrates that the Wisconsin River floodplain was an active N sink, that denitrification often drives N losses, and that enhancing connections between rivers and their floodplains may enhance overall retention and reduce N exports from large basins.

Annotation:

This study evaluated nitrogen transformations during natural river flooding and experimental nitrogen addition experiments. Results suggest substantial capacity for nitrate-N removal from surface water during flood recession.

Implications for enhancing nitrogen attenuation

- Seasonal differences in nitrogen retention in this study (lower retention in springtime) suggest temperature and biological activity is important in nitrogen retention
- Repeated flooding or changes in wetland water levels affect nitrogen retention so water level (and/or its control by human intervention) may be important factors to consider in efforts to enhance nitrogen removal

Gold, A.J., Jacinthe, P.M., Wright W.R. and R.H. Puffer. 1998. Patchiness in groundwater nitrate removal in a riparian forest. *Journal of Environmental Quality* 27, pp. 147-155.

- Riparian zones
- Rhode Island, USA
- Mesocosm experiments with cores from the field
- Reported groundwater flow and NO_3-N in cores from poorly drained and moderately well drained sites

Abstract:

Our ability to identify and manage riparian sites for groundwater nitrate (NO_3^-) removal is limited by uncertainty surrounding the relative importance of plant uptake vs. microbially mediated removal processes. Microcosm studies often demonstrate negligible transformation rates in the subsoil of riparian forests, even in situations where groundwater well networks showed substantial groundwater NO_3^- removal during the winter and a decline in dissolved oxygen (DO) in ambient groundwater moving through the site. We hypothesize that microcosm studies may miss groundwater transformations that occur within microsites, that is, "hotspots" of riparian subsoils. We created mesocosms of large (15 cm diam. × 40 cm length), undisturbed cores from the seasonally saturated zone of poorly drained (PD) and moderately well drained (MWD) sandy soils from a forested riparian area in southern New England. We dosed the mesocosms for 130 d with ambient groundwater amended with NO_3^-–N and Br^-. Changes in the NO_3^-–N/Br^- ratios were used to calculate groundwater NO_3^-–N removal rates. The PD treatment demonstrated substantial groundwater NO_3^-–N removal rates. The PD mesocosms contained patches of dark-stained material that often surrounded roots in various stages of decay. The dry mass of patches in the PD treatment ranged from 0.07 to 1.4% of the mesocosms. The MWD treatment contained no patches and exhibited no groundwater NO_3^-–N removal. Further investigations on the relationships between the extent of subsurface patchiness, water table dynamics and plant characteristics might yield fruitful insights into the management of vegetated riparian zones for groundwater NO_3^-–N removal.

Annotation:

This study involved measuring nitrate loss from large sediment cores in a 120-day mesocosm experiment. As noted in the abstract the aim was to use experimental units large enough to capture denitrification activity in 'hotspots'. Denitrification activity was higher in poorly drained soils with patches of organic matter. The authors note that even larger experimental units may be required to capture denitrification activity in riparian zones. Though the mesocosms were large enough to capture patches, these varied considerably in the PD soils. In addition, there appears to be significant variation in activity in patches. The mesocosm with the highest mass of patch material did not show the highest nitrate loss rate. Nitrate removal rates were generally lower than those found in field experiments. The authors note a potential reason: in the field root turnover and root exudates may serve as a routine source of C replenishment to the shallow groundwater. In addition, in the field NO_3^- is susceptible to plant uptake as well as microbial processing.

Kellogg, D.Q., Gold, A.J., Groffman, P.M., Addy, K., Stolt, M.H., and G. Blazejewski. 2005. In situ ground water denitrification in stratified, permeable soils underlying riparian wetlands. *Journal of Environmental Quality* 34, pp. 524-533.

- Forested riparian zone
- Southern Rhode Island
- Field/lab study
- Reported denitrification potential, DO, nitrate-N, DOC, soil C content, silt/clay percent

Abstract:

The ground water denitrification capacity of riparian zones in deep soils, where substantial ground water can flow through low-gradient stratified sediments, may affect watershed nitrogen export. We hypothesized that the vertical pattern of ground water denitrification in riparian hydric soils varies with geomorphic setting and follows expected subsurface carbon distribution (i.e., abrupt decline with depth in glacial outwash vs. negligible decline with depth in alluvium). We measured in situ ground water denitrification rates at three depths (65, 150, and 300 cm) within hydric soils at four riparian sites (two per setting) using a ^{15}N-enriched nitrate "push–pull" method. No significant difference was found in the pattern and magnitude of denitrification when grouping sites by setting. At three sites there was no significant difference in denitrification among depths. Correlations of site characteristics with denitrification varied with depth. At 65 cm, ground water denitrification correlated with variables associated with the surface ecosystem (temperature, dissolved organic carbon). At deeper depths, rates were significantly higher closer to the stream where the subsoil often contains organically enriched deposits that indicate fluvial geomorphic processes. Mean rates ranged from 30 to 120 μg N kg^{-1} d^{-1} within 10 m versus <1 to 40 μg N kg^{-1} d^{-1} at >30 m from the stream. High denitrification rates observed in hydric soils, down to 3 m within 10 m of the stream in both alluvial and glacial outwash settings, argue for the importance of both settings in evaluating the significance of riparian wetlands in catchment-scale N dynamics.

Annotation:

Study examined denitrification rates and correlated them with various site characteristics. Found that correlations of site characteristics with denitrification rates varied with depth. At 65 cm, ground water denitrification rates varied with factors associated with the surface ecosystem (temperature, dissolved organic carbon). At deeper depths denitrification was significantly higher closer to the stream where the subsoil often contains organically enriched deposits that indicate fluvial geomorphic processes such as intermittent flooding events and stream meandering. Denitrification rates in hydric soils were high in both alluvial and glacial outwash areas, suggesting both soil types are important in nitrogen attenuation.

Implications:

- In surface sediments denitrification may be enhanced by increasing temperatures and dissolved organic carbon content.

- If streams are created or enhanced such that organic deposits are created in deeper soils, denitrification rates are likely to increase in those areas

Mander U., Kuusements, V., Lohmus, D., and T. Mauring. 1997. Efficiency and dimensioning of reiparian buffer zones in agricultural catchments. *Ecological Engineering* 8, pp. 299-324.

Abstract:

A strong linear correlation was found between the log-transformed load and retention of nitrogen and phosphorus in riparian buffer zones ($r = 0.99$ and 0.997, respectively). Analyses of N and P budgets in four riparian forests of varying age (two grey alder stands in Estonia and two riparian deciduous forests in USA) show a significant efficiency. Despite the different input load (72.9–110.4 kg N ha^{-1} $year^{-1}$ and 2.5–3.0 kg P ha^{-1} $year^{-1}$), the outputs into streams from the alder stands systems were comparably low (9.0–13.2 and 0.38–0.62 kg ha^{-1} $year^{-1}$). The older forests from the USA showed less efficiency. Plant uptake of both N and P in younger stands was significantly higher than in older forests. Methods to determine the buffer zones' and buffer strips' width and their efficiency are presented. The testing of efficiency assessment in a watershed in Estonia demonstrated an expected efficiency of buffers. © 1997 Elsevier Science B.V.

Mitch, W.J. and B.C. Reeder. 1994. Nutirent and hydrologic budgets of a Great Lakes coastal freshwater wetland during a drought year. Wetlands Ecology and Management 1(4), pp. 211-222

A coastal wetland along Lake Erie (Ohio, U.S.A.) was studied to determine hydrologic and phosphorus budgets and spatial and temporal variation of phosphorus and related chemical parameters. The wetland was influenced by changing Lake Erie water levels, seiches, shifting shoreline sediments, and watershed inflow during a year of severe drought. The water budget for a 7-month period (March - September, 1988) had average inflow of 15 200 m^3 day^{-1} from the watershed and 3.5 m^3 day^{-1} from Lake Erie. The wetland increased in volume by 700 m^3 day^{-1} despite a drought that resulted in 80% more evapotranspiration than rainfall as a barrier beach isolated the wetland from Lake Erie for 77% of the study period. Conductivity decreased by 34% as water flowed through the wetland and turbidity and total suspended solids were variable and statistically similar at inflow and outflow. Average total phosphorus concentrations in the inflow and outflow were also similar (247 and 248 μg P l^{-1} respectively) although total soluble phosphorus and soluble reactive phosphorus decreased significantly (α=0.05) from inflow to outflow (averages 94 to 45 μg P l^{-1} and 7.5 to 4.0 μg P l^{-1} respectively). Nutrient budgets from field data estimate a retention of 36% of the phosphorus, presumably in the sediments (0.8 mg P m^{-2} day^{-1}). A general nutrient retention model, an estimated deposition rate from a sediment core and a simulation model predicted higher mass retention of phosphorus but similar percentage retention.

Pinay, G., Roques, L., and A. Fabre. 1993. Spatial and temporal patterns of denitrification in a riparian forest. Journal of Applied Ecology 30, pp. 581-591.

- Riparian forest
- River Louge, near Toulouse, France
- Field study

Abstract:

1. This study estimated the importance of *in situ* denitrification in the nitrate buffering capacities of a riparian forest.
2. Spatial and temporal patterns of *in situ* denitrification were investigated along a riparian catena.
3. Highest rates of *in situ* denitrification (up to 78 mg N m^{-2} day^{-1}) were measured in the riparian forest soils in late winter and early spring. Lowest rates (3 mg N m^{-2} day^{-1}) were measured in summer and autumn.
4. Whatever the season considered, 30 m of riparian buffer strip were enough to remove all the nitrates coming through the groundwater.
5. Rehabilitation of riparian zones with riparian vegetation together with the maintenance of waterlogged conditions induced by riverflow regulation appear to be a good point from which to start the restoration of buffering capacities of river ecosystems against nitrogen loads.

Annotation:

Riparian zones are often referred to as "buffer" zones based upon the observation that these locations act as a filter of waters entering streams and rivers. In this paper Pinay et al. investigate the role of microbiological denitrification in riparian zones as a process acting to decrease the nitrate concentrations in waters flowing to forested streams and rivers. This study takes place in the forests bordering the Louge River, upstream of the city of Toulouse in the southwest France. The authors state the importance of soil type, soil topography, vegetation cover, and local hydrology in controlling nitrate supply. They incorporate these parameters into their study with the objective to identify the factors controlling denitrification (a nitrate sink). This spatial and temporal investigation was performed over the course of a year collecting water for nitrate analysis from a series of groundwater sampling wells placed at four different locations along the topographic (and vegetation) gradient from the upland to riparian edge. At each of the four sample sites monthly soil samples were collected for which *in-situ* denitrification rates were quantified.

Based upon the soil denitrification rates and groundwater nitrate concentrations over the course of the year, mean annual rates of denitrification were calculated for the study sites, which indicated high rates of nitrogen loss from the upper soils of the system. Over the course of the year, highest rates of denitrification (nitrogen loss) occurred in the winter and spring (6 mmol N m^{-2} d^{-1}), whereas lowest rates were observed in the summer and autumn (0.2 mmol N m^{-2} d^{-1}). The lowest rates of denitrification corresponded with a period of low ground water elevation and vegetation growth. These finding compare well with the observations of Hill et al (1999) and McHale et al (2002) in the Adirondack Mountains of New York. Spatially, the authors found that nitrate concentrations decreased in the groundwater down the topographic gradient to a point where the concentration was undetectable after 30 m of flow through the riparian zone. These finding lead the authors to conclude that riparian buffer zones are effective at removing nitrate from groundwater entering river systems, and that the restoration and/or implementation of riparian zones provides a buffer against nitrogen loading. These conclusions are interesting, but further investigations into the limit to which these zones can buffer anthropogenic nitrate inputs, in addition to natural sources would be helpful.

Rosenblatt, A.E., Gold, A.J., Stolt, M.H., Groffman, P.M. and D.Q. Kellogg. 2001. Identifying riparian sinks for watershed nitrate using soil surveys. *Journal of Environmental Quality* 30, pp. 1596-1604.

- Riparian zones
- Rhode Island, USA
- Field study
- Reported soil characteristics (redox potential, organic matter, depth of hydric soil, presence/absence of groundwater seeps)

Abstract:

The capacity of riparian zones to serve as critical control locations for watershed nitrogen flux varies with site characteristics. Without a means to stratify riparian zones into different levels of ground water nitrate removal capacity, this variability will confound spatially explicit *source–sink* models of watershed nitrate flux and limit efforts to target riparian restoration and management. We examined the capability of SSURGO (1:15 840 Soil Survey Geographic database) map classifications (slope class, geomorphology, and/or hydric soil designation) to identify riparian sites with high capacity for ground water nitrate removal. The study focused on 100 randomly selected riparian locations in a variety of forested and glaciated settings within Rhode Island. Geomorphic settings included till, outwash, and organic/alluvial deposits. We defined riparian zones with "high ground water nitrate removal capacity" as field sites possessing both >10 m of hydric soil width and an absence of ground water surface seeps. SSURGO classification based on a combination of geomorphology and hydric soil status created two functionally distinct sets of riparian sites. More than 75% of riparian sites classified by SSURGO as organic/alluvium–hydric or as outwash–hydric had field attributes that suggest a high capacity for ground water nitrate removal. In contrast, >85% of all till sites and nonhydric outwash sites had field characteristics that minimize the capacity for ground water nitrate removal. Comparing the STATSGO and SSURGO databases for a 64 000-ha watershed, STATSGO grossly under-represented critical riparian features. We conclude that the SSURGO database can provide modelers and managers with important insights into riparian zone nitrogen removal potential.

Annotation:

This study compared SSURGO classification of riparian features with field measures in forested areas throughout Rhode Island. The definition of high nitrate removal capacity sites was as outlined in the abstract (>10 m of hydric soil width and an absence of ground water surface seeps). This may be useful for classifying Massachusetts riparian areas with a high capacity for nitrate removal.

Rotkin-Ellman, M, Addy, K., Gold, A.J. and P.M. Groffman. 2004. Tree species, root decomposition and subsurface denitrification potential in riparian wetlands. *Plant and Soil* 263, pp. 335-344.

Abstract:

Patches of organic matter have been found to be important 'hotspots' of denitrification in both surface and subsurface soils, but the factors controlling the formation and maintenance of these patches are not well established. We compared the concentration of patches of organic matter and root biomass in the subsurface (saturated zone) beneath poorly drained riparian wetland soils at four sites in Rhode Island, USA - two dominated by red maple (*Acer rubrum*) and two dominated by white pine (*Pinus strobus*). Denitrification enzyme activity (DEA) and carbon (C) content of patch material were compared between sites and between patches with different visual characteristics. Root decomposition was measured in an 8-week ex-situ incubation experiment that compared the effects of water content, root species, and soil matrix origin on CO_2 evolution. We observed significantly greater concentrations of patches at 55 cm at one red maple site than all other sites. DEA and percent C in patches was generally higher in patches than matrix soil and did not vary between sites or by patch type. White pine roots decomposed at a faster rate than red maple roots under unsaturated conditions. Our results suggest that faster root decomposition could result in lower concentrations of patches of organic material in subsurface soils at sites dominated by white pine. Tree species composition and root decomposition may play a significant role in the formation of patches and the creation and maintenance of groundwater denitrification hotspots in the subsurface of riparian wetlands.

Vought, L.B-M., Dahl, J., Pedersen C.L. and J.O. Lacoursiere. 1994. Nutrient retention in riparian ecotones. *Ambio* 23(6), pp. 342-347.

Abstract not available in electronic format.

Annotation:

- Riparian zone
- Various locations in Sweden
- Review article including a compilation of N retention data from the literature
- Presents estimates of nutrient reduction as a function of buffer zone width

This study looks at the effectiveness of buffer strips in reducing nutrient (N and P) loads to streams and rivers. Estimates on nutrient removal are derived from field data from a variety of studies. Results show nitrate retention rates ranging from about 70-100% for buffer strips over 10m wide. Total N reduction ranged from about 40-100% for these buffer strips. The authors note the buffers of 10-20 m can be expected to remove a major part of the nitrogen and phosphorus carried by surface and groundwater flow. In addition, buffer strips provide additional benefits including bank stabilization, shading, and reduction in stream water temperature in hot summer weather.

4.0 STREAMS, RIVERS, LAKES

Alexander, R.B., Smith, R.A. and G.E. Schwarz. 2000. Effect of Stream Channel Size on the Delivery of Nitrogen to the Gulf of Mexico. U. S. Geological Survey, 413 National Center, Reston, Virginia 20192, USA.

Abstract:

An increase in the flux of nitrogen from the Mississippi river during the latter half of the twentieth century has caused eutrophication and chronic seasonal hypoxia in the shallow waters of the Louisiana shelf in the northern Gulf of Mexico1–5. This has led to reductions in species diversity, mortality of benthic communities and stress in fishery resources4. There is evidence for a predominantly anthropogenic origin of the increased nitrogen flux2, 5-7, but the location of the most significant sources in the Mississippi basin responsible for the delivery of nitrogen to the Gulf of Mexico have not been clearly identified, because the parameters influencing nitrogen-loss rates in rivers are not well known. Here we present an analysis of data from 374 US monitoring stations, including 123 along the six largest tributaries to the Mississippi, that shows a rapid decline in the average first-order rate of nitrogen loss with channel size--from 0.45 day1 in small streams to 0.005 day1 in the Mississippi river. Using stream depth as an explanatory variable, our estimates of nitrogen-loss rates agreed with values from earlier studies. We conclude that the proximity of sources to large streams and rivers is an important determinant of nitrogen delivery to the estuary in the Mississippi basin, and possibly also in other large river basins.

Ahlgren, I., Sorensson, F., Waara, T. and K. Vrede. 1994. Nitrogen budgets in relation to microbial transformations in lakes. *Ambio* 23(6), pp. 367-377.

- Lakes
- Lake Vallentuna and Lake Norrviken in Sweden
- Nitrogen budget study
- Provides data on NO3-N, NH4-N, PON, DON, microbial production, and denitrification

Abstract not available in electronic format.

Annotation:

This study examined nitrogen flux and retention in two eutrophic lakes and compared these measures with nitrogen budgets based on measurements of inflows and outflows from the lakes. Microbial denitrification of nitrate to molecular nitrogen and permanent retention in sediments were the most important pathways of nitrogen loss from the lakes. Estimates of denitrification in sediments were made using a 15-N tracer experiment. These measured rates were compared with estimates made using N budget calculations. The two methods gave estimates of the same order of magnitude. The source of the denitrified nitrate was mainly simultaneous nitrification of ammonium. Annual denitrification losses were 5-25% of the external nitrogen loading, which is in the lower range of rates previously reported from lakes. Permanent retention of nitrogen in the sediments of the lakes was 14-33% of the external loading.

Bernhardt, E., Hall, R.O. and G.E. Likens. 2002. Nitrification and nitrate uptake in streams of the Hubbard Brook experimental forest. *Ecosystems* 5, pp. 419-430

Abstract:

Although they drain remarkably similar forest types, streams of the Hubbard Brook Experimental Forest (HBEF) vary widely in their NO_3^- concentrations during the growing season. This variation may be caused by differences in the terrestrial systems they drain (for example, varying forest age or composition, hydrology, soil organic matter content, and so on) and/or by differences between the streams themselves (for example, contrasting geomorphology, biotic nitrogen [N] demand, rates of instream nitrogen transformations). We examined interstream variation in N processing by measuring NH_4^+ and NO_3^- uptake and estimating nitrification rates for 13 stream reaches in the HBEF during the summers of 1998 and 1999. We modeled nitrification rates using a best-fit model of the downstream change in NO_3^- concentrations following short-term NH_4^+ enrichments. Among the surveyed streams, the fraction of NH_4^+ uptake that was subsequently nitrified varied, and this variation was positively correlated with ambient streamwater NO_3^- concentrations. We examined whether this variation in instream nitrification rates contributed significantly to the observed variation in NO_3^- concentrations across streams. In some cases, instream nitrification provided a substantial portion of instream NO_3^- demand. However, because there was also substantial instream NO_3^- uptake, the net effect of instream processing was to reduce rather than supplement the total amount of NO_3^- exported from a watershed. Thus, instream rates of nitrification in conjunction with instream NO_3^- uptake were too low to account for the wide range of streamwater NO_3^-. The relationship between streamwater NO_3^- concentration and rates of instream nitrification may instead be due to a shift in the competitive balance between heterotrophic N uptake and nitrification when external inputs of NO_3^- are relatively high.

Key words: ammonium; nitrate; nitrification; streams; Hubbard Brook Experimental Forest; nutrient cycling; nutrient uptake.

Bernot, M.J. and W.K. Dodds. 2005. Nitrogen retention, removal, and saturation in lotic ecosystems. *Ecosystems* 8, pp. 442-453.

- Streams and rivers
- Various sites throughout the USA
- Review and analysis of data from other studies
- No new field data presented

Abstract:

Increased nitrogen (N) loading to lotic ecosystems may cause fundamental changes in the ability of streams and rivers to retain or remove N due to the potential for N saturation. Lotic ecosystems will saturate with sustained increases in the N load, but it is unclear at what point saturation will occur. Rates of N transformation in lotic ecosystems will vary depending on the total N load and whether it is an acute or chronic N load. Nitrogen saturation may not occur with only pulsed or short-term increases in N. Overall, saturation of microbial uptake will occur prior to saturation of denitrification of N and denitrification will become saturated prior to nitrification, exacerbating increases in nitrate concentrations and in N export downstream. The rate of N export to downstream ecosystems will increase proportionally to the N load once saturation occurs. Long term data sets showed that smaller lotic ecosystems have a greater capacity to remove instream N loads, relative to larger systems. Thus, denitrification is likely to become less important as a N loss mechanism as the stream size increases. There is a great need for long-term studies of N additions in lotic ecosystems and clear distinctions need to be made between ecosystem responses to short-term or periodic increases in N loading and alterations in ecosystem functions due to chronic N loading.

Key words: nitrogen cycle; lotic ecosystems; nitrogen loading; nitrogen retention; denitrification; primary production; nitrification.

Annotation:

This paper describes the processes governing nitrogen retention and removal in lotic ecosystems, and uses USGS data on water chemistry in streams and rivers to test two predictions: 1) the proportion of nitrate to total N will increase with increased nitrogen loading; and 2) the total proportion of N entering the stream channel that is retained will be greatest under low N loading scenarios. Both predictions were supported by the data. The authors note that small streams with high retention time may be most effective at N removal via denitrification.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H. and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29, pp. 59-81.

- Stream
- Data and information taken from various studies in different locations
- Review article
- No data given

Abstract:

The hyporheic zone is an active ecotone between the surface stream and groundwater. Exchanges of water, nutrients, and organic matter occur in response to variations in discharge and bed topography and porosity. Upwelling subsurface water supplies stream organisms with nutrients while downwelling stream water provides dissolved oxygen and organic matter to microbes and invertebrates in the hyporheic zone. Dynamic gradients exist at all scales and vary temporally. At the microscale, gradients in redox potential control chemical and microbially mediated nutrient transformations occurring on particle surfaces. At the stream-reach scale, hydrological exchange and water residence time are reflected in gradients in hyporheic faunal composition, uptake of dissolved organic carbon, and nitrification. The hyporheic corridor concept describes gradients at the catchment scale, extending to alluvial aquifers kilometers from the main channel. Across all scales, the functional significance of the hyporheic zone relates to its activity and connection with the surface stream.

Annotation:

This review looks at the functional significance of the groundwater-stream interface (hyporheic zone) viewed at various spatial scales. Processes including nutrient exchange between groundwater and stream water are discussed. Factors that regulate these processes are described. Impediments to extrapolation across scales are discussed.

Bed permeability and hydrological flow patterns are certainly important variables. At the catchment and reach scales, permeability and flow patterns determine the proportion of discharge through the hyporheic zone, which has been hypothesized to influence how biogeochemical processes in the hyporheic zone affect stream ecosystem metabolism. Ultimately the significance of the hyporheic zone to the surface stream is a function of its activity and extent of connection. Though some fine-scale measurements of certain processes (i.e. nitrification) have been described, it is not clear that these can be extrapolated to reach and catchment scales.

Implications include the following:

- Local conditions determine nitrogen processing in the hyporheic zone, and these vary greatly over relatively small spatial scales
- Fine-scale measures of nitrogen processing can't be extrapolated to describe reach- or catchment-level processes

Boyer, E.W., Goodale, C.L., Jaworski, N.A. and R.W. Howarth. 2002. Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern U.S.A. *Biogeochemistry* 57/58, pp. 137–169.

Abstract:

Human activities have greatly altered the nitrogen (N) cycle, accelerating the rate of N fixation in landscapes and delivery of N to water bodies. To examine relationships between anthropogenic N inputs and riverine N export, we constructed budgets describing N inputs and losses for 16 catchments, which encompass a range of climatic variability and are major drainages to the coast of the North Atlantic Ocean along a latitudinal profile from Maine to Virginia. Using data from the early 1990's, we quantified inputs of N to each catchment from atmospheric deposition, application of nitrogenous fertilizers, biological nitrogen fixation, and import of N in agricultural products (food and feed). We compared these inputs with N losses from the system in riverine export.

The importance of the relative sources varies widely by catchment and is related to land use. Net atmospheric deposition was the largest N source (>60%) to the forested basins of northern New England (e.g. Penobscot and Kennebec); net import of N in food was the largest source of N to the more populated regions of southern New England (e.g. Charles & Blackstone); and agricultural inputs were the dominant N sources in the Mid-Atlantic region (e.g. Schuylkill & Potomac). Over the combined area of the catchments, net atmospheric deposition was the largest single source input (31%), followed by net imports of N in food and feed (25%), fixation in agricultural lands (24%), fertilizer use (15%), and fixation in forests (5%). The combined effect of fertilizer use, fixation in crop lands, and animal feed imports makes agriculture the largest overall source of N. Riverine export of N is well correlated with N inputs, but it accounts for only a fraction (25%) of the total N inputs. This work provides an understanding of the sources of N in landscapes, and highlights how human activities impact N cycling in the northeast region.

Dillon, P.J. and L.A. Molot. 1990. The role of ammonium and nitrate retention in the acidification of lakes and forested catchments. *Biogeochemistry* 11, pp. 23-43.

Abstract. The relative contribution of HNO_3 to precipitation acidity in eastern Canada has increased in recent years leading to some concern that the relative importance of NO_3^- deposition in acidification of terrestrial and aquatic ecosystems may increase. To gauge the extent of this impact, annual mass balances for NO_3^- and NH_4^+ were calculated for several forested catchments and lakes in Ontario. Retention of NH_4^+ (R_{NH_4}) by forested catchments was consistently high compared to retention of NO_3^- (R_{NO_3}) which was highly variable. Retention of inorganic nitrogen was influenced by catchment grade and areal water discharge. In lakes, the reciprocals of retention of NO_3^- and NH_4^+ were linearly related to the ratio of lake mean depth to water residence time ($\bar{z}/\tau$; equal to areal water discharge), and retention did not appear to be a function of degree of acidification of the lakes. Net N consumption-based acidification of lakes, defined as the ratio of annual NH_4^+ mass to NO_3^- mass consumption, was negatively correlated with $\bar{z}/\tau$ and N consumption-related acidification was most likely to occur when $\bar{z}/\tau$ was $< 1.5\,m\,yr^{-1}$.

If retention mechanisms are unaffected by changes in deposition, changes in deposition will still result in changes in surface water concentrations although the changes will be of similar proportions. Therefore, 'NO_3^- saturation' should not be defined by concentrations alone, but should be defined as decreasing long-term, average NO_3^- retention in streams and lakes in response to long-term increases in NO_3^- deposition. Analysis of survey data will be facilitated by grouping lakes and catchments according to similar characteristics.

Gergel, S.E., Carpenter, S.R. and E.H. Stanley. 2005. Do dams and levees impact nitrogen cycling? Simulating the effects of flood alterations on floodplain denitrification. *Global Change Biology* 11, pp. 1352–1367.

Abstract:

A fundamental challenge in understanding the global nitrogen cycle is the quantification of denitrification on large heterogeneous landscapes. Because floodplains are important sites for denitrification and nitrogen retention, we developed a generalized floodplain biogeochemical model to determine whether dams and flood-control levees affect floodplain denitrification by altering floodplain inundation. We combined a statistical model of floodplain topography with a model of hydrology and nitrogen biogeochemistry to simulate floods of different magnitude. The model predicted substantial decreases in NO_3-N processing on floodplains whose overbank floods have been altered by levees and upstream dams. Our simulations suggest that dams may reduce nitrate processing more than setback levees. Levees increased areal floodplain denitrification rates, but this effect was offset by a reduction in the area inundated. Scenarios that involved a levee also resulted in more variability in N processing among replicate floodplains. Nitrate loss occurred rapidly and completely in our model floodplains. As a consequence, total flood volume and the initial mass of nitrate reaching a floodplain may provide reasonable estimates of total N processing on floodplains during floods. This finding suggests that quantifying the impact of dams and levees on floodplain denitrification may be possible using recent advances in remote sensing of floodplain topography and flood stage. Furthermore, when considering flooding over the long-term, the cumulative N processed by frequent smaller floods was estimated to be quite large relative to that processed by larger, less frequent floods. Our results suggest that floodplain denitrification may be greatly influenced by the pervasive anthropogenic flood-control measures that currently exist on most major river floodplains throughout the world, and may have the potential to be impacted by future changes in flood probabilities that will likely occur as a result of climate shifts.

Goodale, C.L., Aber, J.D., and W. McDowell. 2000. The long-term effects of disturbance on organic and inorganic nitrogen export in the White Mountains, New Hampshire. *Ecosystems* 3, pp. 433-450.

- Forested riparian area and streams
- Hubbard Brook area, White Mountains, New Hampshire
- Field Study
- Reported streamflow, nitrogen species including dissolved organic nitrogen, and dissolved organic carbon

Abstract:

The eastern U.S. receives elevated rates of N deposition compared to preindustrial times, yet relatively little of this N is exported in drainage waters. Net uptake of N into forest biomass and soils could account for a substantial portion of the difference between N deposition and solution exports. We quantified forest N sinks in biomass accumulation and harvest export for 16 large river basins in the eastern U.S. with two separate approaches: (1) using growth data from the USDA Forest Service's Forest Inventory and Analysis (FIA) program, and (2) using a model of forest nitrogen cycling (PnET-CN) linked to FIA information on forest age-class structure. The model was also used to quantify N sinks in soil and dead wood, and nitrate losses below the rooting zone. Both methods agreed that net growth rates were highest in the relatively young forests on the Schuylkill watershed, and lowest in the cool forests of northern Maine. Across the 16 watersheds, wood export removed an average of 2.7 kg N ha^{-1} yr^{-1} (range: 1–5 kg N ha^{-1} yr^{-1}), and standing stocks increased by 4.0 kg N ha^{-1} yr^{-1} (3-8 kg N ha^{-1} yr^{-1}). Together, these sinks for N in woody biomass amounted to a mean of 6.7 kg N ha^{-1} yr^{-1} (2–9 kg N ha^{-1} yr^{-1}), or 73% (15–115%) of atmospheric N deposition. Modeled rates of net N sinks in dead wood and soil were small; soils were only a significant net sink for N during simulations of reforestation of degraded agricultural sites. Predicted losses of nitrate depended on the combined effects of N deposition, and both short-and long-term effects of disturbance. Linking the model with forest inventory information on age-class structure provided a useful step toward incorporating realistic patterns of forest disturbance status across the landscape.

Annotation:

This study looked at organic and inorganic nitrogen input and export in old-growth and logged forested watersheds, and tested whether stream export from forests followed early predictions regarding N retention and loss. The authors hypothesized that variation in biotic demand would affect the pattern and magnitude of DIN loss, whereas DON loss would flow patterns of DOC loss. It was expected that biotic control over N Loss would be reflected in seasonal and successional differences in plant and microbial uptake, with elevated DIN losses during the dormant season relative to the growing season and in old-growth stands relative to successional stands. Results showed the organic nitrogen exports correlated with dissolved organic carbon rather than inorganic nitrogen or successional age. Even in old-growth forests, which were expected to export substantial amounts of nitrogen, total nitrogen export was lower than expected (less than 35% of nitrogen inputs). Model results suggest interannual climate variability could partially explain high N retention by influencing microbial N mineralization and plant uptake.

Implications:

- Old-growth forests may retain more nitrogen than expected
- Interannual climate variability may be important in N retention
- DON and DIN show different patterns of retention and loss so analysis of total N retention/loss should take into account processes controlling both

Grimm, N.B., Sheibley, R.W., Crenshaw, C.L., Dahm, C.N., Roach, W.J., and L.H. Zeglin. 2005. N retention and transformation in urban streams. *Journal of the North American Benthological Society* 24(3), pp. 626–642.

Abstract:

Nutrient spiraling in theory and application provides a framework for comparing nutrient retention efficiency of urban streams to relatively unaltered streams. Previous research indicated that streams of the southwestern USA deserts are highly retentive of N because of N limitation, high productivity, and high channel complexity (in particular, extensive transient storage associated with the hyporheic zone). Most southwestern urban streams have extensively modified channels and experience N loading from urban runoff and inputs of NO_3^{-2}-contaminated groundwater. Therefore, we predicted southwestern urban streams are neither N-limited nor retentive. For some urban streams, however, restoration efforts reestablish flow in long-dry channels, create nonstructural flood-management solutions, and design riparian areas as a public recreation amenity. These human modifications may, in part, restore N retention functions if channel complexity and heterogeneity are as important to N retention efficiency as believed. We conducted experimental tracer studies using $^{15}N\text{-}NO_3^{-2}$, as part of the Lotic Intersite Nitrogen eXperiment (LINX) project, and several separate nutrient addition experiments (using slight increases in NO_3^{-2} concentration), to evaluate N retention in southwestern urban streams. We present preliminary results of those experiments, comparing results to similar experiments in unaltered streams to test our predictions. Our results allow an evaluation of the use of nutrient spiraling metrics as a tool for assessing the status of stream ecosystem services in urban restoration projects.

Hall, R.O., Bernhardt, E.S., and G.E. Likens. 2002. Relating nutrient uptake with transient storage in forested mountain streams. *Limnology and Oceanography* 47(1), pp. 155-165.

Abstract:

Streams control the timing and delivery of fluvial nutrient export from watersheds, and hydraulic processes such as transient storage may affect nutrient uptake and transformation. Although we expect that hydraulic processes that retain water will increase nutrient uptake, the relationship between transient storage and nutrient uptake is not clear. To examine this relationship, we injected a conservative tracer and nutrients (ammonium and phosphate) into 13 streams for a total of 37 injections at Hubbard Brook Experimental Forest (HBEF), New Hampshire. Transient storage was estimated by fitting conservative solute data to a one-dimensional advection, dispersion, transient storage model. To correct for variation in depth and velocity among streams, we considered nutrient uptake as a mass-transfer coefficient (*Vf*), which estimates benthic demand for nutrients relative to supply. Transient storage decreased with increasing specific discharge (discharge per unit stream width). Transient storage explained only 14% of variation in ammonium *Vf* during the entire year and 35% of variation during summer months. Phosphate uptake was not related to transient storage, presumably because P uptake is predominantly by chemical sorption at HBEF. At HBEF, surface water pools can store water but were not modeled as such by use of the transient storage model. These pools were probably not important areas of nutrient uptake; further variation in the relationship between nutrient uptake and transient storage may be explained by biological demand.

Hamilton, S.K., Tank, J.L., Raikow, D.F., Wollheim, W.M., Peterson, B.J., and J.R. Webster. 2001. Nitrogen uptake and transformation in a Midwestern US stream: a stable isotope enrichment study. *Biogeochemistry 54, pp. 297-340.*

Abstract. This study presents a comprehensive analysis of nitrogen (N) cycling in a second-order forested stream in southern Michigan that has moderately high concentrations of ammonium (mean, 16 μg N/L) and nitrate (17 μg N/L). A whole-stream $^{15}NH_4^+$ addition was performed for 6 weeks in June and July, and the tracer ^{15}N was measured downstream in ammonium, nitrate, and detrital and living biomass. Ancillary measurements included biomass of organic matter, algae, bacteria and fungi, nutrient concentrations, hydraulic characteristics, whole-stream metabolism, and nutrient limitation assays. The results provide insights into the heterotrophic nature of woodland streams and reveal the rates at which biological processes alter nitrogen transport through stream systems.

Ammonium uptake lengths were 766–1349 m and uptake rates were 41–60 μg N m^{-2} min^{-1}. Nitrate uptake could not be detected. Nitrification rates were estimated from the downstream increase in ^{15}N-enriched nitrate using a simulation model. The ammonium was removed by nitrification (57% of total uptake), heterotrophic bacteria and fungi associated with detritus (29%), and epilithic algae (14%). Growth of algae was likely limited by light rather than nutrients, and dissolved O_2 revealed that the stream metabolism was heterotrophic overall (P:R = 0.2). Incubations of detritus in darkened chambers showed that uptake of ^{15}N was mostly heterotrophic.

Microbial N in detritus and algal N in epilithon appeared to reach isotopic steady state with the dissolved ammonium, but the isotopic enrichment of the bulk detritus and epilithon did not approach that of ammonium, probably due to a large fraction of organic N in the bulk samples that was not turning over. The actively cycling fraction of total N in organic compartments was estimated from the isotopic enrichment, assuming uptake of ammonium but not nitrate, to be 23% for epilithon, 1% for fine benthic organic matter, 5% for small woody debris, and 7% for leaves. These percentages agree with independent estimates of epilithic algal biomass, which were based on carbon:chlorophyll ratios in bulk samples and in algal fractions separated by density-gradient centrifugation in colloidal silica, and of microbial N in the detritus, which were based on N released by chloroform fumigations.

Hill, A.R. and K. Sanmugadas. 1985. Denitrification rates in relation to stream sediment characteristics. *Water Research* 19(12), pp. 1579-1586.

- Riparian area near three rivers
- Southern Ontario, Canada
- Field/lab study (sediment core experiments)
- Reported pH, nitrogen species, organic carbon, soluble carbon, C/N ratio, sediment characteristics

Abstract:

Potential rates of nitrate removal were studied in sediments from three Ontario rivers that differed in texture, organic carbon contents and other characteristics. Intact 0-5 cm depth sediment cores from 22 sites on each river were overlain with aerated 5 mg I- ~ NO~--N solution and incubated in the laboratory at 21°C for 48 h. Rates of nitrate-N loss from the overlying solutions varied from 37 to 412 mg m -2 day-~ for a 24 h incubation period. The acetylene blockage technique was used with nitrate amended sediments to evaluate the relative importance of denitrification and nitrate reduction to ammonium. Denitrification accounted for 80-100% of the nitrate loss in the majority of sediment samples tested. Rates of nitrate loss for the 24 h period exhibited a highly significant positive correlation (r = 0.82q).89) with the water-soluble carbon content of the sediments in each river. Significant relationships were also observed between nitrate loss and organic carbon, total nitrogen and sediment ammonium. A decline in nitrate loss via denitrification and increased nitrate reduction to ammonium was correlated with the organic carbon and water-soluble carbon content of the stream sediments.

Annotation:

Study looked at nitrate removal from sediments in rivers, and correlated this with sediment properties. Nitrate loss correlated with carbon content and ammonium concentration. Variability was high within and between study sites.

Implications:

- Sediment properties, particularly carbon content, greatly affect denitrification rates
- Variability on a small scale suggests results from one small area should not be extrapolated to entire regions

Hill, A.R., Vidon, P.G.F. and J. Langat. 2004. Denitrification potential in relation to lithology in five headwater riparian zones. *Journal of Environmental Quality* 33, pp. 911-919.

Abstract:

The influence of riparian zone lithology on nitrate dynamics is poorly understood. We investigated vertical variations in potential denitrification activity in relation to the lithology and stratigraphy of five headwater riparian zones on glacial till and outwash landscapes in southern Ontario, Canada. Conductive coarse sand and gravel layers occurred in four of the five riparian areas. These layers were thin and did not extend to the field–riparian perimeter in some riparian zones, which limited their role as conduits for ground water flow. We found widespread organic-rich layers at depths ranging from 40 to 300 cm that resulted from natural floodplain processes and the burial of surface soils by rapid valley-bottom sedimentation after European settlement. The organic matter content of these layers varied considerably from 2 to 5% (relic channel deposit) to 5 to 21% (buried soils) and 30 to 62% (buried peat). Denitrification potential (DNP) was measured by the acetylene block method in sediment slurries amended with nitrate. The highest DNP rates were usually found in the top 0- to 15-cm surface soil layer in all riparian zones. However, a steep decline in DNP with depth was often absent and high DNP activity occurred in the deep organic-rich layers. Water table variations in 2000–2002 indicated that ground water only interacted frequently with riparian surface soils between late March and May, whereas subsurface organic layers that sustain considerable DNP were below the water table for most of the year. These results suggest that riparian zones with organic deposits at depth may effectively remove nitrate from ground water even when the water table does not interact with organic-rich surface soil horizons.

Jansson M.R., Leonardson, L. and J. Fejes. 2000. Denitrification and nitrogen retention in a farmland stream in southern Sweden. *Ambio* 23(6), pp. 326-331.

- Stream
- River Raan, Southern Sweden
- Field study
- Reported total N, nitrogen retention, denitrification rate, water discharge, and water temperature

Abstract not available in electronic format.

Annotation:

This study reports on ailed study of a small stream, River Raan in southern Sweden. Mass-balance calculations were done along a 7-km reach with running water and in a small pond. Denitrification activity and limitng factors for denitrification wer analyzed. Total annual nitrogen retention was less than 3% of the total nitrogen transport in the stream. In the pond nitrogen retention was greater than the rest of the river. Significant retention of nitrogen (20-50%) was found to occur during low flow periods in the summer. On such occasions denitrification losses corresponded to more than half of the ottal nitrogen retention. On an annual basisi denitrification was responsible for 30-40% of the total retention in the Raan river. Water detention time was by far the most important factor in determining nitrogen retention in both the river and the pond.

Lovett, G.M., Weathers, K.C., and W.V. Sobczak. 2000. Nitrogen saturation and retention in forested watersheds of the Catskill Mountains, New York. *Ecological Applications* 10(1), pp. 73-84.

Abstract. The Catskill Mountains of southeastern New York receive relatively high rates of atmospheric N deposition, and NO_3^- concentrations in some streams have increased dramatically since the late 1960s. We measured the chemistry of 39 first- and second-order streams with forested watersheds to determine the variability of nitrogen concentrations within the Catskill Mountain area. We found that some streams have low NO_3^- concentrations throughout the year, some have seasonal cycles of varying amplitude, and some have relatively high concentrations year round. If the concentration and seasonality of NO_3^- in stream water are used as indices of nitrogen saturation, then most stages of nitrogen saturation are evident in our survey of Catskill watersheds. Organic nitrogen was a small portion of the total nitrogen for streams with high NO_3^- concentration, but organic N was the dominant form of N (up to 73% of the total) in the streams with lowest nitrate. Estimated retention of N in these watersheds (based on total N in stream water) ranged from 49% to 90% of the atmospheric input. The variation in stream water NO_3^- concentration and the amplitude of the seasonal fluctuations did not appear to be attributable to differences among watersheds in atmospheric deposition, watershed topography, or groundwater influx to the stream. We hypothesize that differences among watersheds in forest species composition and forest history, which are interrelated, produce most of the variation in NO_3^- concentration that we observed.

Mulholland, P.J. 1992. Regulation of nutrient concentrations in a temperate forest stream: roles of upland, riparian, and in-stream processes. Limnology and Oceanography 37(7), pp. 1512-1526.

Abstract:

The roles of terrestrial and instream processes in controlling stream-water N and P concentrations were studied over a 2-yr period in a deciduous forest stream in eastern Tennessee. Upper soil horizons were highly effective sinks for inorganic N and P in throughfall, and weathering of the parent dolomite was the

dominant source of inorganic P to the stream. The riparian zone was a potential source of NH,+ and P to the stream when dissolved oxygen concentrations in riparian groundwater were low, but a sink for P when dissolved oxygen concentrations were high. High rates of instream immobilization of inorganic N and P were observed from late autumn to spring, primarily as a result of uptake by microbes on decomposing leaves and secondarily by algae. Immobilization of inorganic N and P resulted in longitudinal declines in concentrations with distance downstream from groundwater inputs (springs), thereby increasing the importance of organic forms of these nutrients in stream water in downstream reaches. The seasonal pattern of winter minima and summer maxima in stream-water N and P concentrations observed here is opposite to the pattern observed in many northern streams, suggesting the importance of winter nutrient cycling processes in soils and streams in warmer climates.

Mulholland, P.J., Tank, J.L., Sanzone, D.M., Wollheim, W.M., Peterson, B.J., Webster, J.R., and J.L. Meyer. 2000. Nitrogen cycling in a forest stream determined by a ^{15}N tracer addition. *Ecological Monographs* 70(3), pp. 471-493.

Abstract. Nitrogen uptake and cycling was examined using a six-week tracer addition of ^{15}N-labeled ammonium in early spring in Walker Branch, a first-order deciduous forest stream in eastern Tennessee. Prior to the ^{15}N addition, standing stocks of N were determined for the major biomass compartments. During and after the addition, ^{15}N was measured in water and in dominant biomass compartments upstream and at several locations downstream. Residence time of ammonium in stream water (5–6 min) and ammonium uptake lengths (23–27 m) were short and relatively constant during the addition. Uptake rates of NH_4 were more variable, ranging from 22 to 37 $\mu g\ N \cdot m^{-2} \cdot min^{-1}$ and varying directly with changes in streamwater ammonium concentration (2.7–6.7 $\mu g/L$). The highest rates of ammonium uptake per unit area were by the liverwort *Porella pinnata,* decomposing leaves, and fine benthic organic matter (FBOM), although epilithon had the highest N uptake per unit biomass N.

Nitrification rates and nitrate uptake lengths and rates were determined by fitting a nitrification/nitrate uptake model to the longitudinal profiles of ^{15}N-NO_3 flux. Nitrification was an important sink for ammonium in stream water, accounting for 19% of the total ammonium uptake rate. Nitrate production via coupled regeneration/nitrification of organic N was about one-half as large as nitrification of streamwater ammonium. Nitrate uptake lengths were longer and more variable than those for ammonium, ranging from 101 m to infinity. Nitrate uptake rate varied from 0 to 29 $\mu g \cdot m^{-2} \cdot min^{-1}$ and was ~1.6 times greater than assimilatory ammonium uptake rate early in the tracer addition. A sixfold decline in instream gross primary production rate resulting from a sharp decline in light level with leaf emergence had little effect on ammonium uptake rate but reduced nitrate uptake rate by nearly 70%.

At the end of the addition, 64–79% of added ^{15}N was accounted for, either in biomass within the 125-m stream reach (33–48%) or as export of ^{15}N-NH_4 (4%), ^{15}N-NO_3 (23%), and fine particulate organic matter (4%) from the reach. Much of the ^{15}N not accounted for was probably lost downstream as transport of particulate organic N during a storm midway through the experiment or as dissolved organic N produced within the reach. Turnover rates of a large portion of the ^{15}N taken up by biomass compartments were high (0.04–0.08 per day), although a substantial portion of the ^{15}N in *Porella* (34%), FBOM (21%), and decomposing wood (17%) at the end of the addition was retained 75 d later, indicating relatively long-term retention of some N taken up from water.

In total, our results showed that ammonium retention and nitrification rates were high in Walker Branch, and that the downstream loss of N was primarily as nitrate and was controlled largely by nitrification, assimilatory demand for N, and availability of ammonium to meet that demand. Our results are consistent with recent ^{15}N tracer experiments in N-deficient forest soils that showed high rates of nitrification and the importance of nitrate uptake in regulating losses of N. Together these studies demonstrate the importance of ^{15}N tracer experiments for improving our understanding of the complex processes controlling N cycling and loss in ecosystems.

Peterson, B.J., Wollheim, W.M., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., Martı´, E., Bowden, W.B., Valett, H.M., Hershey, A.E., McDowell, W.H., Dodds, W.K., Hamilton, S.K., Gregory, S., and D.D. Morrall, 2001. Control of nitrogen export by headwater streams. *Science* 292, pp. 86-90. www.sciencemag.org

Abstract:

A comparative ^{15}N-tracer study of nitrogen dynamics in headwater streams from biomes throughout North America demonstrates that streams exert control over nutrient exports to rivers, lakes, and estuaries. The most rapid uptake and transformation of inorganic nitrogen occurred in the smallest streams. Ammonium entering these streams was removed from the water within a few tens to hundreds of meters. Nitrate was also removed from stream water but traveled a distance 5 to 10 times as long, on average, as ammonium. Despite low ammonium concentration in stream water, nitrification rates were high, indicating that small streams are potentially important sources of atmospheric nitrous oxide. During seasons of high biological activity, the reaches of headwater streams typically export downstream less than half of the input of dissolved inorganic nitrogen from their watersheds.

Rysgaard, S., Risgaard-Petersen, N., Sloth, N.P., Jensen, K. and L.P.Nielsen. 1994. Oxygen regulation of nitrification and denitrification in sediments. Limnology and Oceanography 39(7), pp. 1643-1652.

Oxygen regulation of nitrification and denitrification in sediments was investigated with ^{15}N-isotope techniques. Sediment cores were incubated in a continuous flowthrough system in which the O_2 concentration was varied in the overlying water while the NO_3^- concentration was kept constant. Nitrification was stimulated with increasing O_2 concentrations in the overlying water from 0 to 100% of atmospheric saturation, whereas only a slight stimulation was observed above 100%. At O_2 concentrations below 100% of atmospheric saturation, NO_3^- from the overlying water was the most important source of N for denitrification, whereas above 100% of atmospheric saturation, NO_3^- produced by nitrification was the main source of N for denitrification. The converse effects of the O_2 levels on the source of NO_3^- can be explained by applying a simple one-dimensional model: O_2 in the overlying water controls the diffusional distance of NO_3^- to the anoxic zone of denitrification and consequently the location of NO_3^- vertically in the sediment as well as the magnitude of the nitrification activity. Our results suggest that in aquatic environments containing low NO_3^- concentrations in the overlying water (such as coastal waters), higher O_2 conditions will stimulate denitrification, while the opposite will occur in systems containing high NO_3^- concentrations (such as eutrophic lakes and streams).

Saunders, D.L. and J. Kalff. 2001. Nitrogen retention in wetlands, lakes, and rivers. *Hydrobiologia* 443, pp. 202-212.

- Rivers, lakes, and wetlands
- Data from various ecosystems in USA, Canada, and Europe
- Review article based on field data
- Reports average annual N retention as a function of nitrogen loading

Abstract

As human activities continue to alter the global nitrogen cycle, the ability to predict the impact of increased nitrogen loading to freshwater systems is becoming more and more important. Nitrogen retention is of particular interest because it is through its combined processes (denitrification, nitrogen sedimentation and uptake by aquatic plants) that local and downstream nitrogen concentrations are reduced. Here, we compare the magnitude of nitrogen retention and its components in wetlands, lakes and rivers. We show that wetlands retain the highest proportion of total nitrogen loading, followed by lakes and then rivers. The differences in the proportion of N retained among systems is explained almost entirely by differences in water discharge. Denitrification is the primary mechanism of nitrogen retention, followed by nitrogen sedimentation and uptake by aquatic plants.

Annotation:

Study compares wetlands, lakes and rivers with respect to nitrogen retention rates. S ummary data from a 23 wetlands, 23 lakes and 5 rivers is used to establish the relationship between nitrogen inputs and retention, and also between nitrogen retention and wetland type. Results show that, for a given total nitrogen load, wetlands retain almost twice the nitrogen as lakes. In general the proportion of nitrogen retained by rivers was found to be minimal. Denitrification accounted for 63% of nitrogen retention in these systems, while sedimentation was responsible for 37%. Once differences in water discharge rates were taken into account, there were no longer significant differences in the nitrogen retention capacities of wetlands, lakes, and rivers.

Implications:

- Increasing water retention time is a key process for promoting nitrogen retention

Seitzinger S.P., Styles, R.V., Boyer, E.W., Alexander, R.B., Billen, G., Howarth, R.W., Mayer, B., and N. Van Breemen. 2002. Nitrogen retention in rivers: model development and application to watersheds in northeastern USA. *Biogeochemistry 57/58, pp. 199-237.*

Abstract. A regression model (RivR-N) was developed that predicts the proportion of N removed from streams and reservoirs as an inverse function of the water displacement time of the water body (ratio of water body depth to water time of travel). When applied to 16 drainage networks in the eastern U.S., the RivR-N model predicted that 37% to 76% of N input to these rivers is removed during transport through the river networks. Approximately half of that is removed in 1st through 4th order streams which account for 90% of the total stream length. The other half is removed in 5th order and higher rivers which account for only about 10% of the total stream length. Most N removed in these higher orders is predicted to originate from watershed loading to small and intermediate sized streams. The proportion of N removed from all streams in the watersheds (37–76%) is considerably higher than the proportion of N input to an individual reach that is removed in that reach (generally <20%) because of the cumulative effect of continued nitrogen removal along the entire flow path in downstream reaches. This generally has not been recognized in previous studies, but is critical to an evaluation of the total amount of N removed within a river network. At the river network scale, reservoirs were predicted to have a minimal effect on N removal. A fairly modest decrease (<10 percentage points) in the N removed at the river network scale was predicted when a third of the direct watershed loading was to the two highest orders compared to a uniform loading.

- Riverine ecosystems
- Mostly eastern US, Canada and western Europe
- Regression model developed based on published data from various
- No field data presented

Annotation:

A regression model was built to predict the proportion of N removed from streams and reservoirs as an inverse function of the water displacement time of the water body (ratio of water body depth to water time of travel). When applied to 16 drainage networks in the eastern US, the model predicted that 37-76% of N input to the rivers is removed during transport through the river networks. Approximately half of the N is removed in 1st through 4th order streams which account for 90% of the total stream length. The other half is removed in 5th order or higher rivers which account for only about 10% of total river length. Most N removed in the higher orders is predicted to originate from watershed loading to small and intermediate sized streams. The proportion of N removed from all streams in the watersheds (37-76%) is considerably higher than the proportion of N input to an individual reach that is removed in that reach (generally <20%) because of the cumulative effect of continued nitrogen removal along the entire flow path in downstream reaches. The authors note that this has not generally been recognized in previous studies, but that it is critical to an evaluation of the total amount of N removed within a river network. At the river network scale, reservoirs were predicted to have a minimal effect on N removal. A fairly modest decrease (<10%) in the N removed at the river network scale was predicted when a third of the direct watershed loading was to the two highest orders compared to a uniform loading.

Tank, J., Meyer, J.L., Sanzone, D.M., Mulholland, P.J., Webster, J.R., Peterson, B.J., Wollheim, W.L., and N.E. Leonard. 2000. Analysis of nitrogen cycling in a forest stream during autumn using a $^{15-}$N tracer addition. *Limnology and Oceanography* 45(5), pp. 1013-1029.

Abstract

We added $^{15}NH_4Cl$ over 6 weeks to Upper Ball Creek, a second-order deciduous forest stream in the Appalachian Mountains, to follow the uptake, spiraling, and fate of nitrogen in a stream food web during autumn. A priori predictions of N flow and retention were made using a simple food web mass balance model. Values of $\delta^{15}N$ were determined for stream water ammonium, nitrate, dissolved organic nitrogen, and various compartments of the food web over time and distance and then compared to model predictions.

Ammonium uptake lengths were shortest at the beginning of the tracer addition (28 m) and increased through time (day 20 = 82 m, day 41 = 94 m), and ammonium residence time in stream water ranged from 4 min on day 0 to 15 min on day 41. Whole-stream ammonium uptake rates, determined from the decline in $^{15}NH_4$ in water over the stream reach, decreased from 191 mg N m^{-2} d^{-1} on day 0 to 83.2 mg N m^{-2} d^{-2} on day 41. Temporal trends in the NH_4 mass transfer coefficient (v_f) were similar to uptake rates; v_f was highest on day 0 (7.4×10^{-4} m s^{-1}) and lower on days 20 and 41 (2.7 and 2.8×10^{-4} m s^{-1}, respectively). Rates of nitrification were estimated to be very low throughout the tracer addition and accounted for <3% of $^{15}NH_4$ uptake on day 0.

It appears that most of the N in epilithon was actively cycling based on comparisons of ^{15}N in stream water and biomass at the end of the experiment. In contrast, for allochthonous organic matter, we found that microbial ^{15}N represented 69% of the label in wood, 20% in leaves, and 31% in fine benthic organic matter (FBOM). Despite higher $\delta^{15}N$ values in primary producers, $^{15}NH_4$ uptake rates per unit stream bottom area were generally lower in epilithon compared to the detrital compartments, a result of the lower biomass of epilithon. Turnover times were

Willett, V.B., Reynolds, B.A., Stevens, P.A., Ormerod, S.J., and D.L. Jones. 2004. Dissolved Organic Nitrogen Regulation in Freshwaters. *Journal of Environmental Quality* 33, pp. 201–209.

Abstract:

Dissolved organic nitrogen (DON) has been hypothesized to play a major role in N cycling in a variety of ecosystems. Our aim was to assess the seasonal and concentration relationships between dissolved organic carbon (DOC), DON, and NO_3^- within 102 streams and 16 lakes within catchments of differing complexity situated in Wales. Further, we aimed to assess whether patterns of land use, soil type, and vegetation gave consistent trends in DON and dissolved inorganic nitrogen (DIN) relationships over a diverse range of catchments. Our results reinforce that DON constitutes a significant component of the total dissolved N pool typically representing 40 to 50% of the total N in streams and lakes but sometimes representing greater than 85% of the total dissolved N. Generally, the levels of DON were inversely correlated with the concentration of DIN. In contrast to DIN concentrations, which showed distinct seasonality, DON showed no consistent seasonal trend. We hypothesize that this reflects differences in the bioavailability of these two N types. The amount of DON, DOC, and DIN was significantly related to soil type with higher DON export from Histosol-dominated catchments in comparison with Spodosol-dominated watersheds. Vegetation cover also had a significant effect on DON concentrations independent of soil type with a nearly twofold decrease in DON export from forested catchments in comparison with nonforested watersheds. Due to the diversity in catchment DON behavior, we speculate that this will limit the adoption of DON as a broad-scale indicator of catchment condition for use in monitoring and assessment programs.

Windolf, J.E Jeppesen, Jensen, J.P. and P. Kristensen. 1996. Modelling of seasonal variation in nitrogen retention and in-lake concentration: a four, pp. 25-44.

Abstract. The mass balance for total nitrogen (N) was studied over a four-year period in 16 shallow mainly eutrophic 1st order Danish lakes. Water was sampled in the main inlet of each lake 18–26 times annually, and from the outlets and the lake 19 times annually. Water was also sampled from minor inlets, although less frequently. N input and output were calculated using daily data on discharge (Q), the latter being obtained either from the Q/H relationship based on automatic recordings of water level (H) for the main in- and outlet, or by means of Q/Q relationships for the minor inlets. Annual mean N retention in the lakes ranged from 47 to 234 mg N m^{-2} d^{-1}, and was particularly high in lakes with high N loading. Annual percentage retention ($N_{ret-y\%}$) ranged from 11 to 72%. Non-linear regression analysis revealed that hydraulic retention time and mean depth accounted for 75% of the variation in annual mean $N_{ret-y\%}$ and, in combination with inlet N concentration, accounted for 84% of the variation in the in-lake N concentration. $N_{ret\%}$ varied according to season, being higher in the second and third quarter than in the first and fourth quarter (median 18–19%). A simple model was developed for predicting monthly nitrogen retention (N_{ret-m}) on the basis of external N loading, the lake water pool of nitrogen N_{pool}, hydraulic loading and lake water temperature. Calibration of only two parameters on data from the randomly selected 8 out of 16 lakes rendered the model capable of accurately simulating seasonal dynamics of the in-lake N concentration and N_{ret-m} in all 16 lakes. We conclude that with regard to shallow, eutrophic lakes with a relatively low hydraulic retention time, it is now possible to determine not only annual mean nitrogen retention, but also the seasonal variation in N_{ret-m}. Prediction of seasonal variation in N loading of downstream N-limited coastal areas is thereby rendered much more reliable.

Wollheim, W.M., Peterson, B.J., Deegan, L.A., Hobbie, J.E., Hooker, B., Bowden, W.B., Edwardson, K.J., Arscott, D.A., Hershey, A.E., and J. Finlay. 2001. Influence of stream size on ammonium and suspended particulate nitrogen processing. Limnology and Oceanography 46(1), pp. 1-13.

Abstract

We used $^{15}NH_4$ tracer additions to determine travel distances of ammonium (NH_4) and suspended particulate organic nitrogen (SPON) in six streams ranging from second to fifth order located within a single watershed on the North Slope of Alaska. Based on the distribution of ^{15}N stored in stream bottom compartments (primary producers or grazers), we estimated NH_4 travel lengths. We used a two-compartment model to estimate the travel length of SPON based on the distribution of source ^{15}N on the stream bottom and $SPO^{15}N$ in the water column. Both NH_4 and SPON travel lengths (S_w and S_p, respectively) increased with discharge primarily due to changes in depth and velocity. Variation in the vertical mass transfer coefficient (v_f) of both NH_4 and SPON did occur among the streams but was not related to stream size and was relatively small compared to the change in physical characteristics. Thus, in the Kuparuk watershed, physical gradients outweighed biological or chemical changes as controls on NH_4 and SPON travel length. The one exception was the Kuparuk fertilized reach, where phosphorus fertilization greatly increased biological activity and NH_4 processing compared to unaltered streams. Longitudinal gradients in major biological driving variables such as litter inputs, debris dams, and shading are absent in the Arctic, perhaps explaining the relatively uniform NH_4-v_f. Watersheds in other biomes may show differing degrees of physical versus biological/chemical controls. A conceptual model is presented for comparing the relative strength of these controls among different watersheds. Strong relationships between discharge and travel length should greatly aid development of watershed models of nutrient dynamics.

5.0 ESTUARIES

Bowden, W.B. 1984. Nitrogen and phosphorus in the sediments of a tidal, freshwater marsh in Massachusetts. *Estuaries* 7(2), pp. 108-118.

ABSTRACT: Total organic nitrogen (TON) and phosphorus (TOP) were measured as a function of depth in 14 cores taken from a New England, tidal, freshwater marsh. TON and TOP ranged from 1.56 to 1.97% and 0.11 to 0.30% of dry weight sediments, respectively. The variation in both pool sizes over time was small and TON varied inconsistently with depth; however, TOP decreased regularly down to 20 cm. Consequently, the TON:TOP ratio increased linearly from 14:1 at the surface to 32:1 at 20 cm, then was nearly constant to 70 cm. This pattern may be a general feature of marsh sediments and may indicate 1) that phosphorus is recycled less efficiently than nitrogen, 2) that over time proportionately more nitrogen than phosphorus is incorporated into recalcitrant compounds, or 3) that phosphorus is more mobile than nitrogen in these marsh sediments. The total inorganic nitrogen pool was measured in this marsh also and was dominated by ammonium (97% of total). The annual average free ammonium concentration was 3.70 ± 0.64 mg N per l at the surface and decreased to 0.92 ± 0.18 mg N per l at 20 to 22 cm in the sediments. Sorption-desorption studies showed that, on a fresh sediment volume basis, sediment sorbed ammonium was roughly equivalent to free porewater ammonium (K = 0.8). The relationship between free and sorbed ammonium was linear between 0.4 and 24.0 mg NH_4-N per l of pore water. The depth distribution of ammonium in these sediments is probably maintained by a dynamic balance between net microbial mineralization of litter, plant uptake, transpiration, diffusion, and porewater advection.

Bowden, W.B. 1986. Nitrification, nitrate reduction, and nitrogen immobilization in a tidal freshwater marsh sediment. *Ecology* 67(1), pp. 88-99.

Abstract. The dominant microbial transformations of ammonium and nitrate in the sediments of a tidal freshwater marsh were estimated from measured rates of isotope dilution of ammonium[^{15}N] added to sediment and litter samples, reduction of nitrate[^{15}N] to ammonium[^{15}N] in fresh sediments, and net exchange of ammonium and nitrate between the marsh and river water in flumes built in the field. In two separate laboratory experiments, nitrification in mixed, fresh, surface sediments was 2.8 and 3.4 $nmol \cdot cm^{-3} \cdot h^{-1}$. In undisturbed field sediments, nitrification rates are probably <1 $nmol \cdot cm^{-3} \cdot h^{-1}$. Additions of nitrate[^{15}N] to fresh sediments showed that nitrate produced from ammonium by nitrification was reduced very quickly. Less than 10% of this nitrate was reduced back to ammonium by dissimilation. The net transfer of nitrate in this marsh is to the sediments, and since nitrate does not accumulate in these sediments, the remaining nitrate produced by nitrification must be reduced by denitrification or by assimilatory nitrate reduction.

Ammonium was removed quickly from filtered and aerated river water that was mixed with plant litter in laboratory incubations. Ammonium-N removal from experimental flasks (215 $nmol \cdot g^{-1} \cdot h^{-1}$) was dependent on the presence of litter and was biologically mediated, but was not due to nitrification since nitrate concentrations were constant in the same experiments. Under anaerobic conditions, ammonium-N was released from litter to river water (93 $nmol \cdot g^{-1} \cdot h^{-1}$). The estimated total rate of ammonium-N immobilization by microbes on aerobic litter (130 $\mu mol \cdot m^{-2} \cdot h^{-1}$) agrees well with measured losses of ammonium from river water in field flume studies (156 $\mu mol \cdot m^{-2} \cdot h^{-1}$). An aerobic litter layer may enable marshes to regulate the loss of ammonium that is regenerated in reduced, subsurface sediments and that would otherwise be lost by diffusion or advection. For example, during portions of the year, excess ammonium may be immobilized on plant litter in aerobic surface layers. Some of this litter is incorporated into reduced subsurface sediments where, later, microbial mineralization may regenerate the immobilized nitrogen. The importance of this nitrogen recycling process in a particular marsh will depend on the degree to which litter is mineralized in place or exported from the marsh before it is incorporated into the reduced sediment, as well as the extent to which plant roots can take advantage of the regenerated nitrogen. If conditions are favorable (low export fraction, low litter C:N ratio, and advantageous root distribution) then mineralization may supply a major portion of the annual plant requirement for nitrogen in excess of that stored in perennial tissues. Both internal recycling and translocation make the plant community less dependent on nitrogen imported from the river.

Nowicki, B.L. 1994. The effect of temperature, oxygen, salinity, and nutrient enrichment on estuarine denitrification rates measured with a modified nitrogen gas flux technique. *Estuarine, Coastal, and Shelf Science* 38, pp. 137-156.

Abstract:

Nitrogen gas flux was measured from sediments taken from Narragansett Bay, Rhode Island, Boston Harbour, Massachusetts, and the Pawcatuck River Estuary, Rhode Island. In addition to studies of field cores taken directly from these systems, intact sediments were taken from Narragansett Bay and maintained in control and nutrient enriched mesocosms. Sediment denitrification was measured as a flux of N_2 gas from sediments in N_2-free chambers. The advantages of this technique are that it allows for the direct measurement of denitrification in undisturbed sediment cores under ambient conditions of dissolved nutrients, oxygen, and temperature. The challenge of this technique has been to correctly distinguish between N_2 fluxes produced by denitrification activity and fluxes of N_2 caused by sediment porewater de-gassing. In this study, anoxic 'control' cores were used to provide continuous checks on the magnitude of porewater de-gassing rates, and allowed measured rates of total N_2 flux to be corrected for this background flux. The use of anoxic control cores allowed measurements to begin soon after core collection, without the need for long pre-incubations.

Observed rates of sediment denitrification ranged from 0 to 195 μmol $N_2\, m^{-2}\, h^{-1}$. Highest rates were found in the enriched mesocosms and at a sewage outfall site in Boston Harbour. Denitrification rates increased exponentially with temperature and were enhanced by added nutrients. Results from the anoxic control cores showed that even after 10 days, the background flux of N_2 from de-gassing porewaters (10–34 μmol $N_2\, m^{-2}\, h^{-1}$) remained a significant fraction of the overall N_2 flux.

Although rates of sediment denitrification were stimulated by added nutrients, the overall percentage loss of N from these systems through denitrification did not keep pace with N enrichment, generally accounting for less than 20% of N inputs. Thus denitrification may not necessarily provide a significant pathway for alleviating eutrophication effects in coastal waters.

Ogilvie, B., Nedwell, D.B., Harrison, R.M., Robinson, A, and A. Sage. 1997. High nitrate, muddy estuaries as nitrogen sinks: the nitrogen budget of the River Colne estuary (United Kingdom). *Marine Ecology Progress Series* 150, pp. 217-228.

Abstract not available electronically

Reay, W.G., Gallagher, D.L., and G.M. Simmons Jr. 1995. Sediment-water column oxygen and nutrient fluxes in nearshore environments of the lower Delmarva Peninsula, USA. *Marine Ecology Progress Series* 118, pp. 215-227.

Abstract not available electronically

Risgaard-Petersen, N. 2003. Coupled nitrification-denitrification in autotrophic and heterotrophic estuarine sediments: On the influence of benthis microalgae. *Limnology and Oceanography* 48(1), pp. 93-105.

Abstract:

Field data obtained from 18 European estuaries using the isotope pairing technique were analyzed for trends in relationship between activity of benthic microalgae and coupled nitrification–denitrification. Kruskal–Wallis tests and analyses of covariance performed on the field dataset showed strong statistical evidence for the hypothesis that sediments colonized by microalgae whose activity exceeds community respiration display lower rates of coupled nitrification–denitrification than do heterotrophic sediments. In fully heterotrophic sediments, 90% of the measurements fell within the range 0–92 μmol N m^{-2} h^{-1} with a median of 20.3 μmol N m^{-2} h^{-1}. In highly autotrophic sediments, 90% of the measurements fell within the range 0–34 μmol N m^{-2} h^{-1}, and the median was 4.2 μmol N m^{-2} h^{-1}. The hypothesis was tested experimentally using ^{15}N and microsensor (NO_3^-) techniques in prepared microcosms with and without algal activity. The results of the experimental studies were consistent with the hypothesis derived from the field data analysis. For the ^{15}N study, coupled nitrification–denitrification in alga-colonized sediments was between 4 and 51% of the activity in sediments without algae activity, depending on the N load. For the microsensor study, there was no indication of net NO_3^- production in alga-colonized sediments before addition of NH_4^+. In contrast, NO_3^- accumulated in the oxic zone of a similar alga-free sediment. The experiments furthermore showed that compared to heterotrophic sediment, the presence of active microalgae might reduce the population of nitrifying bacteria capable of having an active metabolism. These bacterial populations could display diurnal variations in activity correlated with the diurnal variations in O_2 penetration depth, however. The results showed that induction of nitrogen limitation of the nitrifying bacteria population is a major controlling mechanism of coupled nitrification–denitrification in alga-colonized sediments.

Seitzinger, S.P. 1988. Denitrification in freshwater and coastal marine ecosystems: Ecological and geochemical significance. *Limnology and Oceanography* 33(4), pp. 702-724.

- Sediments
- Various locations globally
- Literature review
- Reports summary data from various studies

Abstract:

Denitrification occurs in essentially all river, lake, and coastal marine ecosystems that have been studied. In general, the range of denitrification rates measured in coastal marine sediments is greater than that measured in lake or river sediments. In various estuarine and coastal marine sediments, rates commonly range between 50 and 250 μmol N m^{-2} h^{-1}, with extremes from 0 to 1,067. Rates of denitrification in lake sediments measured at near-ambient conditions range from 2 to 171 μmol N m^{-2} h^{-1}. Denitrification rates in river and stream sediments range from 0 to 345 μmol N m^{-2} h^{-1}. The higher rates are from systems that receive substantial amounts of anthropogenic nutrient input. In lakes, denitrification also occurs in low oxygen hypolimnetic waters, where rates generally range from 0.2 to 1.9 μmol N $liter^{-1}$ d^{-1}. In lakes where denitrification rates in both the water and sediments have been measured, denitrification is greater in the sediments.

The major source of nitrate for denitrification in most river, lake, and coastal marine sediments underlying an aerobic water column is nitrate produced in the sediments, not nitrate diffusing into the sediments from the overlying water. During the mineralization of organic matter in sediments, a major portion of the mineralized nitrogen is lost from the ecosystem via denitrification. In freshwater sediments, denitrification appears to remove a larger percentage of the mineralized nitrogen. N_2 fluxes accounted for 76–100% of the sediment–water nitrogen flux in rivers and lakes, but only 15–70% in estuarine and coastal marine sediments. Benthic N_2O fluxes were always small compared to N_2 fluxes.

The loss of nitrogen via denitrification exceeds the input of nitrogen via N_2 fixation in almost all river, lake, and coastal marine ecosystems in which both processes have been measured.

Denitrification is also important relative to other inputs of fixed N in both freshwater and coastal marine ecosystems. In the two rivers where both denitrification measurements and N input data were available, denitrification removed an amount of nitrogen equivalent to 7 and 35% of the external nitrogen loading. In six lakes and six estuaries where data are available, denitrification is estimated to remove an amount of nitrogen equivalent to between 1 and 36% of the input to the lakes and between 20 and 50% of the input to the estuaries.

Annotation:

The author Seizinger, who specializes in nitrogen biogeochemistry and measuring rates of denitrification in coastal and estuarine environments, has put together this comprehensive literature review of denitrification in various types of freshwater and marine ecosystems. This review provides a good characterization of the process and controls on denitrification, and the ranges of denitrification rates in the various environments. Data from reviewed studies are presented in tables along with references. This review serves as a good reference point for estimating denitrification rates for a particular type of environment although specific differences may exist. In general, the Seitzinger review discusses three types of wetland systems that pertain to the MA DEP project: 1) rivers/streams, 2) lakes, and 3) estuaries (coastal marine). As stated in the abstract, these systems commonly experience denitrification rates ranging from 0-345 µmol N m^{-2} h^{-1} in rivers/streams, 2-171 µmol N m^{-2} h^{-1} in lakes, and 50-250 µmol N m^{-2} h^{-1} in coastal marine ecosystems. A denitrification rate range and annual average (39-109 [59] µmol N m^{-2} h^{-1}) for Narragansett Bay was presented in Table 1 that may be useful to this project. Seitzger continues her review with discussion on the biogeochemical controls of denitrification.

Seitzinger, S.P. and S.W. Nixon. 1985. Eutrophication and the rate of denitrification and N_2O production in coastal marine sediments. *Limnology and Oceanography* 30(6), pp. 1332-1339.

- Estuary
- Narragansett Bay, RI, USA
- Field and laboratory study

Abstract:

Abstract—Large (13 m^3, 5 m deep) microcosms with coupled pelagic and benthic components were used to measure the effect of nutrient loading and eutrophication in coastal marine ecosystems on the rates of benthic denitrification (N_2) and N_2O production. After 3 months of daily nutrient addition, average denitrification rates ranged from about 300 μmol N m^{-2} h^{-1} in the sediments of the control microcosm to 880 in the most enriched microcosm, which received 65 times the nutrient input of the control. Increases in the production of N_2O were more dramatic and increased by a factor of about 100, from 0.56 μmol N m^{-2} h^{-1} in the control to 51 in the most enriched microcosm. Although there was a clear increase in the denitrification rate in the more eutrophic systems, the amount of fixed nitrogen removed was a constant or progressively smaller fraction of the nitrogen input. Even in the most enriched microcosm, at least 16% of the N input was removed by denitrification.

Annotation:

Previously, Seitzinger et al. (1980) identified denitrification as an important sink for fixed nitrogen in Narragansett Bay and removes half of the inorganic loading to the estuary each year from urban sewage. In light of these findings, Seitzinger and Nixon use a laboratory experiment to assess the ability of Narragansett Bay to remove nitrogen (denitrification and N_2O) under eutrophic conditions. The experiment was performed using microcosms filled with native water and sediments, and measured flux across the sediment-water interface. In general, this study showed that N_2 fluxes increased (denitrification was enhanced) with increased nutrient input treatments. Table 1 lists the nitrogen inputs and the associated fluxes of N_2, N_2O, NO_x, sediment nitrification, and O_2 consumption. Average denitrification rates in the control (308 µmol N m^{-2} h^{-1}) and the 4x treatment (302 µmol N m^{-2} h^{-1}) did not significantly differ, yet the larger increases in nitrogen input did cause a significant increase in denitrification rates (16x treatment, 555 µmol N m^{-2} h^{-1}). Nitrification accounted for part of the nitrogen fraction removed by denitrification. One important issue highlighted by the authors was that the absolute rates observed in the microcosm experiments were about two-three times those rates occurring in the natural Narragansett Bay system under similar nutrient loads, the cause for this trend was unknown. The main relationship identified in this experiment was that denitrification removed a constant or progressively smaller fraction of the nitrogen input. The authors state that if this relationship holds in the natural environment, it is clear that the capacity of estuaries and other nearshore systems to remove anthropogenic nitrogen loading through denitrification is limited.

Seitzinger, S., Nixon, S., Pilson, M.E.Q., and S. Burke. 1980. Denitrification and N_2O production in near-shore marine sediments. *Geochimica et Cosmochimica Acta* 44, pp. 1853-1860.

Abstract—Methods were developed for determining rates of denitrification in coastal marine sediments by measuring the production of N_2 from undisturbed cores incubated in gas-tight chambers. Denitrification rates at summer temperatures (23°C) in sediment cores from Narragansett Bay, Rhode Island, were about 50 μmol N_2 m^{-2} hr^{-1}. This nitrogen flux is equal to approximately one-half of the NH_4^+ flux from the sediments at this temperature and is of the magnitude necessary to account for the anomalously low N/P and anomalously high O/N ratios often reported for benthic nutrient fluxes. The loss of fixed nitrogen as N_2 during the benthic remineralization of organic matter, coupled with the importance of benthic remineralization processes in shallow coastal waters may help to explain why the availability of fixed nitrogen is a major factor limiting primary production in these areas. Narragansett Bay sediments are also a source of N_2O, but the amount of nitrogen involved was only about 0.2 μmol m^{-2} hr^{-1} at 23°C.

Shaver, G.R. and J.M. Melillo. 1984. Nutrient budgets of marsh plants: efficiency concepts and relation to availability. *Ecology* 65(5), pp. 1491-1510.

- Tidal freshwater marsh
- North River, Hanover, MA
- Field and laboratory study on marsh plant species

Abstract:

Abstract. The effects of variable N and P availability on nutrient uptake, nutrient recovery from dying leaves, and biomass production in three species of marsh graminoids were studied in a growth chamber experiment. "Availability" was defined as the total amount of N or P added to each pot over the duration of the experiment. The species were *Carex lacustris, Calamagrostis canadensis,* and *Typha latifolia.* Responses were evaluated in terms of three "efficiencies": (1) efficiency of uptake, or the proportion of available N or P taken up by the plants; (2) efficiency of recovery, or the removal of nutrients from dying leaves as a proportion of the N or P content of mature leaves; and (3) efficiency of use, or the ratio of total biomass to total N or P mass in the whole plant. In all three species, as N or P availability increased, all three efficiency indexes decreased. There was evidence for N × P interaction in regulating efficiency of N or P uptake, but not the other two indexes. Implications for ecosystem nutrient cycling are discussed, with the conclusion that, as nutrient inputs to an ecosystem increase, nutrient losses from the system and nutrient turnover in the vegetation should also increase.

Annotation:

Shaver and Melillo present the results of an experiment that investigated nutrient uptake of nitrogen and phosphorus in three common freshwater marsh graminoids. The plants were all collected from the North River estuary in Hanover, MA, therefore the results of the authors' laboratory experiments are applicable to other freshwater estuarine marshes in Massachusetts that contain similar plants. Shaver and Melillo specifically evaluated the nutrient efficiency of the three plants. These efficiencies encompass the nutrient cycling processes of the plants, which occur in conjunction with those in the sediments. In terms of assessing the nitrogen attenuation of a freshwater marsh, this paper explains the manner in which nitrogen is taken up and cycled in plant biomass. The experiments were performed by fertilizing the potted plants with controlled amounts of nitrogen and phosphorus, and harvesting entire plant samples (live and dead material) at two times during the experiment to quantify biomass, nutrient uptake, and nutrient content within the plant material.

6.0 SALT MARSHES, MUDFLATS

Addy, K., Gold, A., Nowicki, B., McKenna, J., Stolt, M., and P. Groffman. 2005. Denitrification capacity in a subterranean estuary below a Rhode Island fringing salt marsh. *Estuaries* 28(6), pp. 896-908.

- Salt marsh
- Coastal Rhode Island
- Field study
- Measured denitrification capacity in-situ

Abstract:

Coastal waters are severely threatened by nitrogen (N) loading from direct groundwater discharge. The subterranean estuary, the mixing zone of fresh groundwater and sea water in a coastal aquifer, has a high potential to remove substantial N. A network of piezometers was used to characterize the denitrification capacity and groundwater flow paths in the subterranean estuary below a Rhode Island fringing salt marsh. 15N-enriched nitrate was injected into the subterranean estuary (in situ push-pull method) to evaluate the denitrification capacity of the saturated zone at multiple depths (125–300 cm) below different zones (upland-marsh transition zone, high marsh, and low marsh). From the upland to low marsh, the water table became shallower, groundwater dissolved oxygen decreased, and groundwater pH, soil organic carbon, and total root biomass increased. As groundwater approached the high and low marsh, the hydraulic gradient increased and deep groundwater upwelled. In the warm season (groundwater temperature, 12 °C), elevated groundwater denitrification capacity within each zone was observed. The warm season low marsh groundwater denitrification capacity was significantly higher than all other zones and depths. In the cool season (groundwater temperature, 10.5 °C), elevated groundwater denitrification capacity was only found in the low marsh. Additions of dissolved organic carbon did not alter groundwater denitrification capacity suggesting that an alternative electron donor, possibly transported by tidal inundation from the root zone, may be limiting. Combining flow paths with denitrification capacity and saturated porewater residence time, we estimated that as much as 29-60 mg N could be removed from 1 l of water flowing through the subterranean estuary below the low marsh, arguing for the significance of subterranean estuaries in annual watershed scale N budgets.

Annotation:

Study examined in-situ denitrification rates in a salt marsh. Showed strong seasonal effect as well as an effect from tidal exchange and salinity changes.

Implications for the retention in wetlands include the following:

- Seasonal Effect: Warm season and cold season denitrification rates likely vary a great deal
- Estuarine effect: Tidal inundation and salinity changes affect nitrogen retention and denitrification rates. The effectiveness of any given nitrogen retention strategy depends on local conditions – factors including temperature (season), frequency of inundation with seawater, and other factors can affect nitrogen cycling, nitrogen removal and retention in the ecosystem.

Bertness, M.D., P.J. Ewanchuk, and B.R. Silliman. 2002. Anthropogenic Modification of New England Salt Marsh Landscapes. Proceedings of the National Academy of Science 99:1395-1398.

Abstract:

Salt marshes play a critical role in the ecology and geology of wave-protected shorelines in the Western Atlantic, but as many as 80% of the marshes that once occurred in New England have already been lost to human development. Here we present data that suggest that the remaining salt marshes in southern New England are being rapidly degraded by shoreline development and eutrophication. On the seaward border of these marshes, nitrogen eutrophication stimulated by local shoreline development is shifting the competitive balance among marsh plants by releasing plants from nutrient competition. This shift is leading to the displacement of natural high marsh plants by low marsh cordgrass. On the terrestrial border of these same marshes, shoreline development is also precipitating the invasion of the common reed, *Phragmites,* by means of nitrogen eutrophication caused by the removal of the woody vegetation buffer between terrestrial and salt marsh communities. As a consequence of these human impacts, traditional salt marsh plant communities and the plants and animals that are dependent on these habitats are being displaced by monocultures of weedy species.

Cabrita, M.T. and V. Brotas. 2000. Seasonal variation in denitrification and dissolved nitrogen fluxes in intertidal sediments of the Tagus estuary, Portugal. *Marine Ecology Progress Series* 202, pp. 51-65.

- Estuary, mudflat
- Tagus Estuary, Lisbon, Portugal
- Field and laboratory study
- Measurements of DIN fluxes and denitrification across sediment-water interface

ABSTRACT: Dissolved nitrogen fluxes and denitrification were studied during 1 yr in intertidal sediments of the Tagus estuary (Portugal). This study focused on the factors regulating both nitrogen fluxes across the sediment-water interface and denitrification, and on the effect of microphytobenthos activity in controlling nitrogen cycling in these areas. Sampling was performed monthly at 2 stations located in inner and outer intertidal areas. Fluxes of O_2, NO_3^-, NO_2^-, NH_4^+ and N_2O, and denitrification (determined by the nitrogen-isotope pairing technique) were measured simultaneously in closed chambers incubated in the laboratory under simulated *in situ* temperature and light conditions, as well as in the dark. At the sediment-water interface, higher DIN fluxes and lower denitrification rates were registered at higher temperatures and lower NO_3^- concentration in the water column. Oxygen uptake by the sediment was generally higher than release, particularly in summer. Primary productivity displayed a seasonal cycle, positively influenced by temperature. Denitrification rates were closely related to NO_3^- river-input. Temperature, NO_3^- concentration in the water column, microphytobenthos, infauna and tidal height were the key parameters involved in controlling nitrogen cycling at the sediment-water interface in the Tagus estuary. A comparison of annual nitrogen fluxes and denitrification rates between sites was made, taking into account tidal immersion periods. Hence, N-removal by denitrification accounted for 156 mmol m^{-2} yr^{-1} in the inner station and 482 mmol m^{-2} yr^{-1} in the outer station. These rates represent respectively ca 3 and 9% of total DIN available in the estuarine water column at those 2 stations, respectively. N_2O production was comparatively very low (0.3 to 0.6 mmol m^{-2} yr^{-1}). The estimated nitrogen assimilation rates by microphytobenthos were 707 mmol m^{-2} yr^{-1} in the inner station and 333 mmol m^{-2} yr^{-1} in the outer station, indicating that a considerable amount of nitrogen was retained within benthic microalgae. The assimilation/denitrification ratio, with a mean value of 2, shows the relative importance of the denitrification role as a N-sink. Apart from denitrification, it is suggested that other processes must be involved in the removal of nitrogen from the estuary.

Annotation:

This study provides a comprehensive investigation into the biogeochemical cycling of nitrogen in an urban estuary. Through the measurement of environmental conditions and O_2, NO_3^-, NO_2^-, NH_4^+, and N_2O fluxes, the authors determined that the controlling parameters over nitrogen cycling in this environment were temperature, nitrate concentration, benthos, and tidal inundation. Denitrification was found to be an important sink of nitrogen, removing between 156 and 482 mmol m^{-2} y^{-1}. However, assimilation of nitrogen by the microphytobenthos (primarily diatoms) was observed to occur at rates higher than denitrification; these rates ranged from 333-707 mmol m^{-2} y^{-1}. Although denitrification was identified as an important nitrogen removal process in the Tagus system, due to the high rates of biological assimilation of nitrogen in the benthos, this process is concluded to be the major nitrogen sink in the estuary.

A seasonal pattern of sediment-water column NO_3^- (DIN) fluxes was observed in this study, an observation consistent with other studies. In summer nitrate was released from the sediments, whereas the opposite was observed in winter. Despite this apparent trend, a considerable amount of variability was observed in the rates of nitrate flux between seasons and between sampling locations. Total denitrification also exhibited a seasonal trend, where rates were highest in winter, lowest in summer. Coupled nitrification-denitrification (D_n) generally accounted for the greatest percentage of total denitrification. Nitrogen loss through denitrification was quantified by measurement of N_2 and N_20. Rates of N_2 loss ranged from 20-250 µmol m^{-2} h^{-1} and rates of N_20 loss ranged from 0.01-0.8 µmol m^{-2} h^{-1}; these rates consistent with research in other systems.

In the Discussion section of this paper the authors do a good job of relating their findings to the biochemical processes that are believed to be taking place in the Tagus Estuary, and compare their findings with other studies. Although this is a common scientific practice, this paper is easy to read, written in a clear, succinct manner. Figure 7 in the discussion provides a useful visual model of the study's results. This model is useful because it breaks down the flux of biogeochemical constituents between the sediments and water column over intertidal sediments, creating a figure for this type of environment which has not been observed elsewhere in the literature.

Dausse, A., Mrot, P., Bouzille, J-B., Bonis, A. and J-C. Lefeuvre. 2005. Variability of nutrient and particulate matter fluxes between the sea and a polder after partial tidal restoration, Northwest France.

Abstract:

This paper aims to investigate the patterns of exchanges of nutrients and suspended sediments between the sea and a polder, after partial tidal restoration, and to assess if these are comparable to those observed in natural salt marshes. The study site, situated in the Bay of Veys, in Northwestern France, was embanked in the 1870s and accidentally reconnected to the sea in 1990. Water now flows in and out of the polder by a single communication point with the sea, which facilitated water sampling and flux calculation for dissolved and particulate elements.

The study was carried out for two years, from May 2002 to April 2004. Results showed that for all the months studied the water flowing out of the polder had lower concentrations of nitrates and suspended sediments, which lead to a retention of these elements throughout the year. Nitrates uptakes in the polder were much higher in winter (up to 473.9 g N ha^{-1} $tide^{-1}$) than in summer where they were close to zero. The retention of suspended sediment could be over 80% of the import and was mainly composed of organic matter. Finally, the concentrations of dissolved organic carbon were higher in outflow than inflow water, but due to unbalanced water budgets this lead to low quantities imported in summer and higher amounts exported for all other seasons. No interpretable pattern was observed for ammonium.

The nature of these fluxes, according to literature, is close to those observed in immature salt marshes, so as far as restoration is concerned, it has been shown that partial tidal restoration can allow the restitution of the salt marsh exchange functions that were studied.

Davis, J.L., Nowicki, B., and C. Wigand. 2004. Denitrification in fringing salt marshes of Narragansett Bay, Rhode Island, USA. *Wetlands* 24(4), pp. 870-878.

- Salt marsh
- Narragansett Bay, Rhode Island, USA
- Field and laboratory study

Abstract:

In the past century, loading of terrestrial inorganic nitrogen to coastal receiving waters has increased dramatically. Salt marshes, because of their location between upland regions and coastal waters and their recognized role as nutrient transformers, have the potential to ameliorate some of this loading. In the current study, we used core incubations in the laboratory to investigate denitrification rates in high marsh soils from five fringing salt marshes in Narragansett Bay, Rhode Island, USA. The marshes showed a wide variety of terrestrial N loading, with rates ranging from 2 to 6037 kg N ha^{-1} yr^{-1}. Field-collected cores were selected to include both vegetated and bare soils at each marsh, and the six-hour incubations were designed to approximate natural tidal rhythms. Total dissolved nitrogen flux in these marshes ranged between +1255 and -710 µmol N m^{-2} hr^{-1}, with N_2 gas accounting for the majority of the total N flux (average 76%). Nitrogen gas flux ranged between -375 (nitrogen fixation) and +420 (denitrification) µmol N_2 m^{-2} hr^{-1}. While N_2 gas fluxes were significantly correlated ($r = +0.64$, $p < 0.05$) with marsh organic carbon content, we also detected a significant inverse relationship ($r = -0.91$, $p < 0.05$) between average N_2 gas fluxes and terrestrial nitrogen loads. Comparison of N_2 gas fluxes in vegetated vs. bare soils indicated a significant ($p < 0.05$) but variable effect of vegetation on N_2 flux. This field survey shows the potential of New England fringe salt marshes to intercept and transform land-derived nitrogen loads; however, sediment characteristics (e.g., percent of labile organic matter) and plant community structure can significantly affect the capacity of the marsh to process inorganic nitrogen loads. In order to understand the role of salt marshes in buffering coastal N loading, we need a better understanding of the natural and anthropogenic factors controlling denitrification and net N losses.

Annotation:

Salt marshes, similarly to riparian zones along rivers and streams, have been recognized as locations where there is the potential to buffer nutrient (e.g. nitrogen) loading to coastal waters. The microbiological process of denitrification provides a mechanism for removing nitrogen dissolved in water, by way of transforming inorganic nitrogen compounds to nitrogen gas. In this light, Davis et al. performed an investigation into the denitrification ability of salt marshes along the heavily populated Narragansett Bay, an estuary that experiences excessive amounts of nitrogen loading. The investigation was performed in the laboratory on high marsh soils collected from five different fringing salt marsh locations within the Bay, resulting in measurements of nitrogen flux between the sediment and overlaying waters and a differentiation between natural and anthropogenic sources of nitrogen loading.

Laboratory analysis results indicated that both denitrification and nitrification was taking place in the marsh sediments, with N_2 gas accounting for the majority of the total N flux (average 76%). Observed denitrification rates reached a maximum of up to 420 µmol N m^{-2} hr^{-1}, a rate higher than observed in other similar systems. Another interesting observation was that the amount of N_2 gas produced (via denitrification) was greater than the amount of nitrate accounted for, implying that the excess rates of denitrification were a product of coupled nitrification-denitrification. Phosphorus fluxes were variable (-3.5 to 7.1 µmol m^{-2} hr^{-1}), with no correlation to nitrogen fluxes. Amounts of dissolved organic carbon (DOC) and oxygen gas uptake were measured. Rates of nitrogen flux were found to be correlated with soil organic content. No correlation was observed for nitrogen flux and the soil oxygen content. Rates of oxygen uptake by sediments were between 17 and 700 µmol m^{-2} hr^{-1}. Also of interest, the authors noted that the sites with the largest terrestrial impact (highest nitrogen loading) incurred net nitrification and lower levels of denitrification, a potential impact of coastal development, although this was proposed to have been caused by a combination of environmental factors, including the development of a bluegreen algal mat and a vegetation species shift from *S. patens* to *S. pungens*. In general, this study has shown that all sediment cores analyzed experienced net nitrate uptake, caused by either denitrification alone, or coupled nitrification-denitrification. This comprehensive investigation should stand as an example of the biogeochemical cycling of nitrogen likely occurring in Massachusetts salt marshes.

Emery, N., P. Ewanchuk, and M.D. Bertness. 2001 Competition and salt-marsh plant zonation: stress tolerators may be dominant competitors. Ecology 82(9): 2471-2485.

- Salt marsh
- Massachusetts
- Field study
- Reports nutrient availability, species composition, plant biomass, tiller height, results of transplanting and fertilizing plots

Abstract. Although a great deal of research has focused on the effects of nutrient supply on plant competition, few studies have explored how these processes interact with non-resource factors to determine community-level patterns. This study examined how resource competition interacts with physical stress to structure salt-marsh plant communities across a natural gradient in tidal stress. First, nutrient additions at naturally occurring species borders at zonal and patch boundaries in two Rhode Island (USA) marshes revealed that competitive outcomes were typically reversed when nutrients were abundant. These results, which are consistent with earlier findings in a third southern New England marsh, suggest that a nutrient-dependent competitive hierarchy is a general characteristic of salt marshes in this region. To test whether these shifts in competitive outcomes occur only at naturally occurring species borders or can lead to more significant shifts in zonation patterns, lower marsh species were transplanted into the matrix of each zonal species at higher tidal elevations, and the outcomes of plant competition in fertilized plots and unfertilized plots were compared. Results of this experiment indicate that nutrient effects on the competitive relations of marsh plants were independent of where the interactions took place along the tidal gradient. The stress-tolerant species were consistently the best competitors in fertilized treatments, showing that an increase in nutrient availability can lead to drastic shifts in the distributions of plants across marshes. Finally, a third experiment examined the interaction between nutrient supply and the above-ground and belowground components of plant competition using a reciprocal transplant design coupled with nutrient-addition and neighbor-removal treatments. Results suggest that competition is primarily belowground under ambient marsh conditions but is aboveground at high nutrient levels. Thus the mechanism underlying the nutrient-dependent competitive hierarchy may be driven by a trade-off between belowground and aboveground competitive abilities, although the potential interaction between above- and belowground effects was not examined. Together, the results of these experiments suggest that nutrient supplies may significantly affect the competitive dynamics between salt-marsh perennials and their resultant zonation across an environmental gradient in tidal stress. The result that stress tolerators can be dominant competitors is not predicted by any current model of plant competition and must be considered in future empirical and theoretical studies.

Annotation:

This study suggests that an increase in nutrient availability can cause a shift in species composition. The implication for nitrogen attenuation efforts is that diverting nutrient-rich water into salt marshes could cause a change in species composition and/or alter competitive interactions between species.

Findlay, S.E.G., Dye, S., and K.A. Kuehn. 2002. Microbial growth and nitrogen retention in litter of *Phragmites australis* compared to *Typha angustifolia*. *Wetlands* 22(3), pp. 616-625.

- Tidal freshwater marsh
- Tivoli North Bay of Hudson River National Estuarine Research Reserve
- Field study
- Sampled reed *Phragmites australis* and cattail *Typha angustifolia*. Measured C, N, P in decay rate, mass loss, fungal production, bacterial production

Abstract: In tidal marshes of the northeast US, replacement of native cattail (*Typha angustifolia*) by the common reed (*Phragmites australis*) is widespread, and reed is often the target of removal efforts. Reed sequesters nearly twice the amount of nitrogen per unit marsh area in living aboveground tissue compared to cattail. Microbial decay processes immobilize additional nitrogen or return this organic nitrogen to the pool of inorganic nitrogen. We compared microbial growth during decay of standing and fallen litter of cattail and reed. Shoots of both plants were collected at the time of peak live biomass and then periodically throughout litter decomposition. Litter was analyzed for mass loss, nitrogen content, and biomass and production of fungi and bacteria. There were statistically significant but small differences in litter-associated microbial biomass and production between these two plants. Microbial production on both litter types was dominated by fungi, accounting for > 99% of the total. Living fungal biomass (estimated from ergosterol) associated with reed and cattail litter averaged 6.1 and 8.2 mg fungal C/g litter dry mass, respectively, and fungal nitrogen accounted for roughly 25% of the total nitrogen associated with litter. Detrital nitrogen standing stocks/m^2 were greater for reed than cattail throughout the first 2.5 years of decay. Therefore, the ability of reed litter to support decomposer growth is only somewhat lower and nitrogen retention is greater than for one of the plants it replaces. These differences are probably insufficient to argue for aggressive control of reed in tidal wetlands.

Annotation:

Reed sequesters about twice as much N per unit marsh area in living aboveground tissue than cattail. Microbial decay processes immobilize additional N or return this organic N to the pool of inorganic N. The study compared microbial growth during decay of standing and fallen litter of cattail and reed. Shoots of both plants were collected at peak biomass and periodically throughout litter decomposition. Litter was analyzed for mass loss, N content and biomass and production of fungi and bacteria. Microbial production on both litter types was dominated by fungi, accounting for over 99% of the total. Living fungal biomass associated with reed and cattail litter averaged 6.1 and 8.2 mg fungal C/g litter dry mass, respectively, and fungal N accounted for about 25% of the total N associated with litter. Detrital N standing stocks per m^2 were greater for reed than cattail. But decomposer growth is lower in reed than cattail. The greater reed biomass compensates for the lower N in decomposer biomass in reed litter such that the quantity of N sequestered in reed litter per unit area is always greater than that of cattail (often several-fold greater). For this reason reed is commonly used in treatment wetlands outside the US.

Hamersley, M.R., and B.L. Howes. 2003. Contribution of denitrification to nitrogen, carbon, and oxygen cycling in tidal creek sediments of a New England salt marsh. *Marine Ecology Progress Series* 262, pp. 55-69.

- Salt marsh
- Mashapaquit Marsh, West Falmouth, MA, USA
- Field study

Abstract:

The contribution of denitrification to sediment metabolism was studied at 2 sites (muddy and sandy) in unvegetated tidal creek sediments from a small Cape Cod, USA, salt marsh receiving nitrate-enriched groundwater flows (32 mmol m^{-2} d^{-1}). Simultaneous measurements of sediment N_2, CO_2, O_2, and dissolved inorganic N fluxes were made over annual cycles. A total of 46% of the ammonium remineralized within the sediments was transformed to N_2 by coupled nitrification-denitrification (D_n). Denitrifying and nitrifying bacteria contributed 15 and 18% to total sediment C and O cycling, respectively. C, N, and O_2 cycling rates were limited by both temperature and the availability of labile organic matter. Muddy sediment C content was twice that of sandy sediments, but was half as labile, resulting in similar mean metabolic rates between sediment types (mean muddy and sandy O_2 consumption rates were 62 and 58 mmol m^{-2} d^{-1}, respectively; CO_2 production was 58 and 46 mmol m^{-2} d^{-1}; and D_n was 5.4 and 4.9 mmol N m^{-2} d^{-1}). Sediment $\delta^{13}C$ (–18.5 and –20.8‰) and the molar CO_2:N flux ratio (6.1) at both sites are consistent with a sediment metabolism based on algal rather than macrophytic biomass, and groundwater nitrate was the dominant source of N supporting algal growth. Annually, D_n accounted for 72% of total denitrification, with the remainder accounted for by water column-supported denitrification. Since all the denitrified N originated from groundwater nitrate, algal uptake must have initially out-competed denitrification for water column nitrate, but nearly half of this algal N was subsequently remineralized and denitrified.

Annotation:

In a paper published prior to Davis et al. (2004) about denitrification capability of salt marshes in Narragansett Bay, RI, Hamersley and Howes (2003) investigated the contribution of denitrification in a Buzzards Bay, MA salt marsh. This study was focused more on the controls of denitrification within a single marsh system, rather than over a regional approach, such as in the various marsh sites of Narragansett Bay.

Similarly to Davis et al. (2004), Hamersley and Howes (2003) found that coupled nitrification-denitrification contributes to the production of N_2 gas. Coupled nitrification-denitrification occurred at 4.9 to 5.4 mmol N m^{-2} d^{-1}, similar to Davis et al. (2004) who sited a maximum denitrification rate of 10.1 mmol N m^{-2} d^{-1}, which included the coupled nitrification-denitrification component. In fact, Hamersley and Howes (2003) state that coupled nitrification-denitrification accounts for 72% of total nitrification. Therefore, based upon that percentage, the authors observed a total denitrification rate of 6.8 to 7.5 mmol N m^{-2} d^{-1}, a rate that is more comparable to the maximum rate observed by Davis et al. (2004). Seasonally, coupled nitrification-denitrification occurred at lower levels in the winter and at its highest in summer. For all sources of nitrate (groundwater as main source, marsh moderate, atmospheric minor) entering the Mashapaquit salt marsh, the denitrification flux was dominated by coupled nitrification-denitrification (1.6 mol N m^{-2} yr^{-1}, 72%), with the remainder by water column denitrification (0.66 mol N m^{-2} yr^{-1}, 28%). A previous study (Smith, 1999) suggested that the Mashapaquit salt marsh removed 12.9 mmol N m^{-2} d^{-1} of the 32 mmol N m^{-2} d^{-1} that were transported to the marsh. Oxygen uptake rates were higher than Davis et al. (2004) (0.41 to 17 mmol m^{-2} d^{-1}). It seems that the rate of coupled nitrification-denitrification in the marsh sediments was primarily controlled by the amount of labile organic carbon available to the nitrogen fixing bacteria, and partially influenced by seasonal effects (temperature). The amount of NO_x^- available for denitrification was also a controlling factor in certain circumstances.

Hamersley M.R. and B.L. Howes. 2004. Nitrogen fluxes and mitigation strategies in the Audubon Skunknett River Wildlife Sanctuary. Report to the Town of Barnstable April 27, 2004.

- Salt marsh
- Mashapaquit Marsh, West Falmouth, MA, USA
- Field study
- Reported residence time, water temperature, PON, POC, chlorophyll-a and phaeophytin, TDN, NO_x, NH_4, PO_4

Abstract: not available electronically.

Annotation:

This study evaluated nitrogen flux from Skunkett River to Scudder Bay, and options for enhancing nitrogen removal by altering the hydrologic regime.

The Skunkett River flows through a wildlife sanctuary where four ponds formerly existed. Whereas the residence time of water in these ponds and wetlands was formerly much longer, the residence time of Skunkett River is now just 2.2 hr. This is insufficient to allow natural N removal processes (i.e. denitrification) to significantly reduce N flux into Scudder Bay. However, retention time and N removal could be enhanced by restoring the former ponds along the river. Using measures of current nitrogen flux and hydrologic regime, it was proposed that restoring the ponds would increase nitrogen loss significantly. Under a scenario of maximum pond restoration the summer total nitrogen removal would be as much as 40%, and dissolved inorganic nitrogen removal up to 73%. The total nitrogen removal would be the equivalent of sewering about 565 houses.

Howes, B.L., P.K.Weiskel, D.D.Goehringer and J.M.Teal. 1996. Interception of freshwater and nitrogen transport from uplands to coastal waters: the role of salt marshes. pp. 287-310 in Estuarine Shores: Evolution and Human Alternations, K.F. Nordstrom and C.J. Roman eds. Wiley, London.

- Salt marsh
- Massachusetts
- Field and lab study
- Reports on groundwater discharge, denitrification in sediment cores, nutrient concentrations in interstitial waters and freshwater inflows, aboveground plant biomass

Annotation:

Salt marshes adjacent to watersheds with highly permeable soils intercept significant amounts of groundwater carrying dissolved inorganic nitrogen (ca 90% nitrate) from terrestrial non-point sources. Groundwater enters the marsh primarily at the upland border and through creekbottoms, both of which have significantly higher permeabilities than the peat underlying most of the vegetated marsh as determined by measurements of salinity and sediment permeability in Namskaket Marsh in Orleans, MA.

Measurements in Great Sippewissett Marsh in Falmouth, MA indicate that most of the nitrate in intercepted freshwater inflows is denitrified within the creekbottom sediments. In the overall nitrogen budget of these salt marshes, NH_4^+ and particulate N export is from the vegetated marsh and is resupplied primarily by N_2 fixation. Interception of terrestrially derived nitrate and its denitrification occurs predominantly within creekbottom sediments, while removal of dissolved inorganic N from flood tidal waters in spring and early summer is likely via short-term incorporation into litter within vegetated marsh areas. The organic matter supporting creekbottom denitrification comes primarily from the vegetated marsh with a contribution from benthic algae. In situ measurements indicate that the dentrification capacity of the creekbottoms is not fully utilized and that rates can increase if nitrate concentrations in groundwater increase. Interception of groundwater transported N and denitrification within creekbottoms represents a mechanism for salt marshes to reduce the potential for eutrophication of adjacent coastal waters as N loading to coastal watersheds increases.

Hussein, A.H. and M.C. Rabenhorst. 2002. Modeling of nitrogen sequestration in coastal salt marsh soils. *Soil Science Society of America Journal* 66, pp. 324-330.

Abstract:

Extensive field-based data from two representative submerged upland tidal marsh soils in the Chesapeake Bay area were gathered to develop a predictive model for total N sequestration. The data covered the range in physiographic position and variation in marsh habitats. Sampling protocol and model validation assure the validity of the model, and placed 80% confidence, and 10% accuracy on the rate of total N sequestration and the predictive model. In coastal marsh ecosystems, total N sequestration continues to occur with time by accumulation in the organic horizons and sea-level rise is the driving force. The predictive model was a two-step linear function indicating accelerated sequestration of total N in the past two centuries. During the last 150 yr, the rate of total N sequestration averaged 4.2 ± 1.15 g m^{-2} yr^{-1}, while over the last one or two millennia the rate of total N sequestration averaged 1.47 ± 0.3 g m^{-2} yr^{-1}. In the next century, modeled prediction of total N sequestration in newly forming marshes averaged 20 ± 7.9 g m^{-2} yr^{-1}. Present and long-term rates of organic S and total N sequestration in coastal marsh ecosystems were comparable as well as their future predictions. Sequestration of total N in terrestrial closed systems and coastal marshes showed similar long-term trends.

Jordan, T.E., Correll, D.L., and D.F. Whigham. 1983. Nutrient flux in the Rhode River: tidal exchange of nutrients by brackish marshes. *Estuarine, Coastal and Shelf Science* 17, pp. 651-667.

- Salt marsh, mudflat
- Rhode River Estuary, MD, USA
- Field study

Abstract:

Tidal exchanges of nitrogen, phosphorus, and organic carbon by a high and a low elevation marsh in the Rhode River estuary were measured throughout the year. Both marshes tended to import particulate matter and export dissolved matter, although they differed in the fluxes of certain nutrients. Compared with tidal exchanges, bulk precipitation was a major source of ammonia and nitrate and a minor source of other nutrients. There was a net retention of nutrients by the portion of the Rhode River that included both marshes and a mudflat. However, the marshes accounted for only 10% of the phosphorus retention and 1% of the nitrogen retention while they released organic carbon amounting to 20% of the retention. This suggests that the mudflat acted as a sink for nutrients. The primary role of the marshes seems to be transformation of particulate to dissolved nutrients rather than nutrient retention or release.

Annotation:

This paper investigates the effect of tidal exchange on nutrient retention in salt marshes and adjacent mudflats in the Chesapeake Bay, MD. As indicated in the abstract, the authors observed that the mudflat acted as a sink for nutrients. This study involved a year long collection data, during 11 tidal cycles, sampling water for nutrient analyses and observing tidal velocities. Based upon nutrient constituent concentrations and tidal velocity, a nutrient flux was calculated. Nutrient fluxes were monitored and calculated over the course of the year to create a budget in the study area's salt marshes and mudflats (Table 3, 4). A detailed summary of net nutrient (phosphorous, nitrogen, carbon) attenuation is provided in Table 5 for the gradient from mudflat, low marsh, and high marsh. Table 5, which is based upon the tidal fluxes of nutrient concentration in water, indicates that mudflats are the primary location for phosphorous, nitrogen, and carbon retention. Groundwater was not investigated, although the balance in tidal exchange led the authors to assume that groundwater input was negligible. Other studies, such as Hamersley and Howes (2003), have indicated that groundwater can provide a significant source for nitrogen. Although no measurements of N_2 gas exchange were made, the net release of nitrogen from the high marsh indicates that nitrification exceeds denitrification in that location, a finding consistent with other studies. There have not been very many studies that have specifically investigated mudflats. The importance of this study is the fact that it highlights the large role and influence that mudflats have on retaining nutrients. Rather than a nutrient flux budget, an *in situ* study of nitrogen exchange should be performed to support these findings. Although technically not a mudflat, the findings from Hamersley and Howes (2003) show that muddy salt marsh creek sediments are also sinks for nitrogen by denitrification. A study similar to the one performed by Hamersley and Howes (2003) would be valuable to mudflat nitrogen cycling research.

Kaplan, W., Valiela, I., and J.M. Teal. 1979. Denitrification in a salt marsh ecosystem. *Limnology and Oceanography* 24(4), pp. 726-734

Abstract not available in electronic format.

Mortimer, R.J.G, Davey, J.T., Krom, M.D., Watson, P.G., Frickers, P.E., and R.J. Clifton. 1999. The effect of macrofauna on the porewater profiles and nutrient fluxes in the intertidal zone of the Humber Estuary. *Estuarine, Coastal and Shelf Science* 48, pp. 683-699.

Abstract:

Macrofauna, nutrient fluxes, porewater chemistry and sediment characteristics were measured at six intertidal mudflat sites in the Humber Estuary, U.K., during the different seasons. *Nereis diversicolor*, *Macoma balthica* and *Corophium volutator* were found to be the dominant macrofauna. Salinity was the baseline control on macrofauna distribution but this was overprinted by periodic impoverishment due to sediment mobilization. High resolution gel probe porewater samplers provided direct evidence for the impact of burrows on porewater chemistry. The macrofauna modified nutrient fluxes during periods of mud flat stability. *Nereis* caused a decrease in silicate and phosphate effluxes but enhanced ammonia release and nitrate uptake. *Macoma* enhanced ammonia and nitrite release. The impact of *Corophium* was not possible to discern. The Humber is a large, highly dynamic macrotidal estuary in which sediment resuspension has a large impact on porewater profiles, nutrient fluxes and macrofaunal communities. Simple patterns and inter-relationships which are seen in small sheltered estuaries are not observed in the Humber.

Mortimer, R.J.G., Krom, M.D., Watson, P.G., Frickers, P.E., Davey, J.T., and R.J. Clifton. 1999. Sediment-water exchange of nutrients in the intertidal zone of the Humber Estuary, UK. *Marine Pollution Bulletin* 37(3-7), pp. 261-279.

Abstract:

Nutrient pore-water profiles, sediment–water exchange and sediment characteristics were measured for six intertidal mudflat sites throughout the Humber Estuary over the different seasons. The Humber is a highly dynamic, non steady state system and hence neither the biogeochemical zones nor the macrofaunal communities were sustained for long periods of time. Sediment mixing and resuspension on tidal, episodic or seasonal timescales was the predominant control on nutrients. Over an annual cycle, mean measured fluxes were −8.7 mmoles/m^2/day nitrate, 3.7 mmoles/m^2/day ammonia and 0.2 mmoles/m^2/day nitrite. Net phosphate and silicate fluxes were very small. The intertidal mudflats were a sink for nitrate (−1000 kmol/day), a major source of ammonia (430 kmol/day) and a minor source of nitrite (25 kmol/day). Nitrate influxes decreased in a seaward direction (−13.4 mmoles/m^2/day in inner estuary, −11.0 mmoles/m^2/day in mid-estuary, −5.2 mmoles/m^2/day in outer estuary), but when the area of the mudflats in each area is taken into account, both the mid and outer estuary were sinks for approximately 40% of the total nitrate taken up. In contrast, the outer estuary was the source of c. 90% of the ammonia and 105% of the nitrite (the inner estuary being a minor sink of nitrite).

Owens, N.J.P. and W.D.P. Stewart. 1983. *Enteromorpha* and the cycling of nitrogen in a small estuary. *Estuarine, Coastal and Shelf Science* 17, pp. 287-296.

Abstract:

The nitrogen relations of *Enteromorpha* spp. growing on intertidal mud flats have been examined over a twelve-month period. Nitrogen assimilation rates using ^{15}N have been used to calculate the production of the alga and were between 0·046 and 0·217 mg NH_4^+–N (g dry wt alga)$^{-1}$ h^{-1}. A considerable quantity of the alga was buried beneath the sediment over the growth season and was calculated to be equivalent to an input of up to 9·52 g N m^{-2} per month and 32 g N m^{-2} over one complete growth season. Based on carbon, this latter value represented an input of approximately 320 g C m^{-2} annually. Low rates of nitrogenase activity (acetylene reduction) were found to be associated with the *Enteromorpha*. The organisms responsible for the nitrogenase activity were probably heterotrophic bacteria but they did not contribute significant quantities of nitrogen to the alga.

Portnoy, J., Nowicki, B.L., Roman, C.T., and D.W. Urish. 1998. The discharge of nitrate-contaminated groundwater from developed shoreline to marsh-fringed estuary. *Water Resources Research* 34(2), pp. 3095-3104.

- Mixed use coastal watershed and fringing salt marsh
- Nauset Marsh, Cape Cod, Massachusetts
- Field/lab study
- Measured salinity, groundwater discharge, hydraulic head, groundwater discharge areas (via thermal imagery) NO3-N, NH4-N, and P04-P

Abstract:

As residential development, on-site wastewater disposal, and groundwater contamination increase in the coastal zone, assessment of nutrient removal by soil and sedimentary processes becomes increasingly important. Nitrogen removal efficiency depends largely on the specific flow paths taken by groundwater as it discharges into nitrogen-limited estuarine waters. Shoreline salinity surveys, hydraulic studies, and thermal infrared imagery indicated that groundwater discharge into the Nauset Marsh estuary (Eastham, Massachusetts) occurred in high-velocity seeps immediately seaward of the upland-fringing salt marsh. Discharge was highly variable spatially and occurred through permeable, sandy sediments during low tide. Seepage chamber monitoring showed that dissolved inorganic nitrogen (principally nitrate) traversed nearly conservatively from the aquifer through shallow estuarine sediments to coastal waters at flux rates of 1–3 mmol m^{-1} h^{-1}. A significant relationship between pore water NO_3-N concentrations and NO_3-N flux rates may provide a rapid method of estimating nitrogen loading from groundwater to the water column.

Annotation:

Study examined spatial and temporal patterns of groundwater discharge and nitrogen flux along shores of low and high residential development density. Potential nitrogen removal at the shoreline interface between the freshwater aquifer and coastal waters was assessed. Results showed groundwater discharged in seeps below mean low water and to a lesser extent above mean low water, and was highly variable over space. Nitrate concentrations in groundwater discharge varied greatly, but reflected up-gradient development. Nitrate was over 30 times higher along developed shores than around an undeveloped embayment. Nitrate concentrations did not show a seasonal pattern, suggesting that temperature-dependent biological activity was not an important factor affecting nitrate discharge.

Implications:

- If nitrate-rich groundwater flows into estuaries via seeps, it circumvents the high denitrification potential of low-redox, highly organic marsh and subtidal sediments
- If groundwater can be re-routed to flow through these areas nitrate removal might take place
- Denitrification in muddy subtidal sediments might be an important factor in promoting nitrogen removal from these systems

Sakamaki, T., Nishimura, O., and R. Sudo. 2006. Tidal time-scale variation in nutrient flux across the sediment-water interface of an estuarine tidal flat. *Estuarine, Coastal and Shelf Science* 67, pp. 653-663.

Abstract:

We determined the range of the tidal variations in nutrient flux across the sediment−water interface and elucidated mechanisms of the flux variation in two estuarine intertidal flats (one sand, one mud) in northeastern Japan. Nutrient flux was measured using in situ light and dark chambers, which were incubated for 2 h, 2−6 times per day. Results showed that nutrient concentration in overlying water varied by tide and was also affected by sewage-treated water inflow. The nutrient fluxes responded quickly to the tidal variation in overlying water chemistry and the range of the variation in flux was as large as the seasonal-scale variation reported in previous studies. In the sand flat, salinity increase likely enhanced benthos respiration and led to increases in both O_2 consumption and PO_4^{3-} regeneration under low illumination, while benthic microalgae were likely to actively generate O_2, uptake PO_4^{3-} and suppress PO_4^{3-} release under high illumination (>900 μmol photons m^{-2} s^{-1}). Also in the mud flat, PO_4^{3-} flux was related with O_2 flux, although the range of temporal variation in PO_4^{3-} flux was small. In both the flats, NH_4^+ flux was always governed by NH_4^+ concentration in the overlying water; either an increase in NH_4^+ uptake or a decrease in NH_4^+ release was observed as the NH_4^+ concentration rose due to inflow of river water or input of sewage-treated water. Although NO_3^- tended to be released in both tidal flats when low NO_3^- concentration seawater dominated, their relationship was likely to be weakened under conditions of low oxygen consumption and suppressed denitrification. It is likely that tidal variation in nutrient flux is governed more by the nutrient concentration than other factors, such as benthic biological processes, particularly in the case where nutrient concentration in the overlying water is relatively high and with wide amplitude.

Silliman, B. R. and M. D. Bertness. 2004. Shoreline Development Drives the Invasion of *Phragmites australis* and the Loss of New England Salt Marsh Plant Diversity. Conservation Biology 18: 1424- 1434.

- Salt Marsh
- New England
- Field experiment
- Data on *Phragmites* cover, soil salinity, nitrogen availability (measured as nitrogen in cordgrass tissue), shoreline development (measured as removal of woody vegetation), and extent of invasion by *Phragmites*

Annotation

This study looked at the interactive role of habitat alteration (i.e. shoreline development) in driving invasion of *Phragmites australis Cav,* and consequences for plant species richness. Twenty-two salt marshes were surveyed and the relationship between development (measured as removal of woody vegetation bordering marshes) and *Phragmites* invasion. Development explained >90% of intermarsh variation in *Phragmites* cover. Development was also correlated with reduced soil salinity and increased nitrogen availability. Together, soil salinity and nitrogen availability explained 80% of the variation in *Phragmites* invasion success. These findings suggest Phragmites invasions could occur with increased nitrogen loading to salt marshes, and indicate the importance of maintaining integrity of salt marsh borders in conserving natural communities.

Thompson, S.P., Paerl, H.A. and M.C. Go. 1995. Seasonal patterns of nitrification and denitrification in a natural and a restored marsh. Estuaries 18(2), pp. 399-408.

- Salt marsh
- Newport River Estuary, NC, USA
- Field and laboratory study

Abstract:

Seasonal patterns of microbially-mediated nitrogen cycling via the nitrification-denitrification pathway were compared between a natural and a restored salt marsh. Sedimentary denitrification rates, measured with a modification of the acetylene block technique, were approximately 44 times greater in the natural marsh relative to an adjacent transplanted marsh. Nitrification rates were similar at both sites. The difference in denitrification rates was attributed to oxygen inhibition at low tide and tidal flushing of porewater nutrients at high tide in the coarse sediments of the restored marsh. Denitrification was positively correlated with nitrification throughout the year in the natural marsh with a seasonal fall peak in denitrification corresponding to a maximum in porewater ammonia concentration. A weak correlation existed between the two processes in the restored marsh, where nitrification rates exceeded denitrification rates by a factor of 20. T ransplanted marsh denitrification rates exhibited a spring peak, corresponding to elevated porewater ammonia concentrations. Our findings demonstrate functional differences in microbial nitrogen dynamics of a young (0-3 yr) restored marsh relative to a mature (>50 yr) salt-marsh system.

Annotation:

This paper presents an investigation of two areas of interest to this literature review: 1) rates of denitrification (nitrogen loss), and 2) a performance comparison of denitrification between a natural and a restored salt marsh. The study takes place on the Newport River near Morehead City, NC. The natural marsh study site is adjacent to the restored marsh site, which was constructed on a former dredge spoil dump site and modeled after the surrounding natural marshes. Both sites' sediments were sampled quarterly for 1.5 years, beginning only 1 year after marsh restoration (*Spartina* transplanting). Nitrogen fertilization treatments were added to select experimental plots. Sediment denitrification, nitrification, porewater ammonium, and redox potential were analyzed in the laboratory.

This study is similar to other salt marsh studies in this bibliography in that the same parameters are monitored and analyzed, this presents a good characterization of the amounts and rates of flux for these constituents in a salt marsh. However, where this study is unique from the others is that a statistical comparison was completed to assess the nitrogen flux of a natural marsh versus a newly constructed/restored marsh, information that may be useful in considering how to best engineer these wetlands to buffer nitrogen loads to the coastal waters.

Rates of denitrification exhibited a seasonal trend with peaks in the autumn, although there was no significant correlation between denitrification and temperature. All denitrification rates monitored in the restored marsh (~16 µmol N m^{-2} d^{-1} average) were roughly two orders of magnitude lower than rates in the natural marsh sediments (~190 µmol N m^{-2} d^{-1} average). On the other hand, nitrification rates were not significantly different in the natural and restored marsh sediments, and these rates exhibited a seasonal trend (highest in summer, lowest in winter). Differences between the denitrification rates in the natural and restored marshes may be due to sediment grain-size (58 % vs. 97% sand in natural and restored, respectively), elevated oxygen concentrations in the restored marsh, and elevated levels of organic material and nitrogen cycling in the natural (mature) marsh. It is clear from this study that newly constructed salt marshes do not cycle nitrogen to the same degree as mature natural salt marshes.

White, D.S. and B.L. Howes. 1994. Long-term 15N-nitrogen retention in the vegetated sediments of a New England salt marsh. *Limnology and Oceanography* 39(8), pp. 1878-1892.

Abstract:

^{15}N was used in a 7-yr field study and a laboratory investigation of a single growing season to quantify the amount, timing, and mechanisms of annual N retention and loss in the plant-sediment system of a short *Spartina alterniflora* marsh. There was an initial rapid loss of ~25% of the added $^{15}NH_4^+$ through nitrification-denitrification at a rate of 25.2 mg N m^{-2} d^{-1}, with the remaining label being incorporated into plant tissues. Label losses decreased throughout the study as ^{15}N was increasingly sequestered in the dead organic N pool. About 40% of the injected label remained after seven growing seasons. Total annual N losses were 7.3–7.6 g N m^{-2} yr^{-1} based on ^{15}N losses and estimates of the actively cycling N pool. Export accounted for 26–44% and denitrification for 54–77% of the total N loss. Burial of N in dead belowground organic matter was 3.7–4.1 g N m^{-2} yr^{-1}, similar to estimates determined from accretion and total sediment N data. Recycling of N through translocation from aboveground to belowground biomass and remineralization of dead belowground biomass was the major pathway in the sediment N cycle, equivalent to 67–79% of the annual plant N demand. Annual N losses were balanced by inputs, primarily N_2 fixation. Long-term N retention appears to be controlled primarily by the competition for DIN between the plants and bacterial nitrifiers-denitrifiers and secondarily by the relative incorporation of N into aboveground vs. belowground biomass.

Wigand, C., McKinney, R., Chintala, M., Charpentier, M., and G. Thursby. 2003. Relationships of nitrogen loadings, residential development, and physical characteristics with plant structure in New England salt marshes. Estuaries 26(6): 1494-1504.

- Salt Marsh
- New England
- Field experiment
- Data on *Spartina* density, extent and height, as well as overall plant species richness

Annotation:

This study examined nutrient availability, development, plant species richness, and the extent, density, and height of *Spartina* species in salt marshes. Significant inverse relationships of tall *S. alterniflora* with species richness and with the extent and density of *S. patens* and short *S. alterniflora* were observed (that is, tall *S. alterniflora* was associated with fewer species and loss of *S. patens*). Extent and density of *S. patens* and extent of short *S. alterniflora* were positively and significantly related with plant species richness. Significant inverse relationships were observed for nitrogen load, percent residential development, and slope with *S. patens,* short *S. alterniflora,* and species richness, and significant positive relationships with tall *S. alterniflora*. Results indicate that increased nitrogen loading may alter competitive interactions and species composition in salt marshes.

7.0 MIXED-USE WATERSHEDS

DeSimone L.A. and B.L. Howes. 1998. Nitrogen transport and transformations in a shallow aquifer receiving wastewater discharge: A mass balance approach. *Water Resources Research* 34(2), pp. 271-285.

- Coastal watershed, sewage treatment plan effluent and groundwater
- Orleans, MA
- Field and lab study
- Measured pH, chloride, alkalinity, PON, DON, NH_4-N, NO_2-N, NO_3-N, TDN, TN, N_2, N_2O, POC, DOC, TOC

Abstract not available electronically.

Annotation:

Nitrogen transport and transformation were followed over the initial 3 years of development of a plume of wastewater-contaminated groundwater. Ammonification and nitrification in the unsaturated zone and ammonium sorption in the saturated zone were predominant, while loss of fixed N through denitrification was minor. The major effect of groundwater transport was oxidation of discharged organic and inorganic forms of N to nitrate. Ammonification and nitrification in the unsaturated zone transformed 16-19% and 50-70% respectively of the total N mass discharged to the land surface during the study, but did not attenuate the nitrogen loading. Nitrification in the unsaturated zone also contributed to a pH decrease of 2 standard units and to an N_2O increase. Denitrification was carbon-limited in the anoxic zone and only reduced about 2% of the recharged nitrogen mass to N_2.

Howes B., Ramsey, J.S. Kelley, S.W., Samimy, R. Schlezinger, D. and E. Eichner. 2005. Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Great/Perch Pond, Green Pond, and Bournes Pond, Falmouth, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection, Boston, MA. 205 pp + Executive Summary, 11 pp

Abstract:

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Great/Perch Pond, Green Pond and Bournes Pond embayment systems, three coastal embayments within the Town of Falmouth, Massachusetts. Analyses of the Great/Perch Pond, Green Pond and Bournes Pond embayment systems was performed to assist the Town with up-coming nitrogen management decisions associated with the Towns' current and future wastewater planning efforts, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayments based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Falmouth resource planning and decision-making process. The primary products of this effort are: (1) a current quantitative assessment of the nutrient related health of the Great/Perch Pond, Green Pond and Bournes Pond embayment systems, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Great/Perch Pond, Green Pond and Bournes Pond embayment systems.

Krieger, K.A. 2003. Effectiveness of a coastal wetland in reducing pollution of a Laurentian Great Lake: hydrology, sediment, and nutrients. *Wetlands* 23(4), pp. 778–791.

Abstract:

The ability of coastal wetlands of the Laurentian Great Lakes to reduce pollution from tributaries has not been documented in detail or over multiple seasons. This study developed a surface-water budget for a coastal wetland along Lake Erie and estimated monthly, annual, and storm-related exports of total suspended solids and selected nutrients from the wetland. Water-budget measurements included precipitation, evaporation, surface discharge into the wetland, and net surface discharge into Lake Erie. Water samples collected upstream and downstream and composite dryfall-precipitation samples were analyzed for total suspended solids (TSS), total phosphorus (TP), soluble reactive phosphorus (SRP), nitrate-nitrite nitrogen (NO_2), ammonia nitrogen (NH_3), total Kjeldahl nitrogen (TKN), soluble reactive silica, chloride, and specific conductance. Seasonal and storm-related concentration patterns and a wide variation in monthly, seasonal, and annual loads from the tributary into the wetland were typical of streams draining the western Lake Erie basin. All substances reached higher maximum concentrations upstream than downstream; however, median monthly time-weighted mean concentrations of TP, TSS, NH_3, and TKN were higher downstream.

Concentrations without discharge data were inadequate to estimate removal rates. Annual loads of TSS, NH_3, and TKN increased during passage through the wetland, whereas those of TP, SRP, NO_2, and soluble reactive silica decreased. During storm runoff events, various proportions of TP, SRP, TSS, NO_2, and soluble reactive silica were removed, despite brief hydraulic residence times, whereas more NH_3 exited than entered. Wetlands occupying the flooded lower reaches of Great Lakes tributaries collectively are probably important in maintaining and enhancing the water and sediment quality of the lakes. Water levels throughout the Laurentian Great Lakes have decreased in recent years; consequently, wetland areas with standing water and hydraulic residence times have decreased, probably reducing the effectiveness of the wetlands in mitigating pollution.

Lajtha, K. 1995. Retention and leaching losses of atmospherically-derived nitrogen in the aggrading coastal watershed of Waquoit Bay, MA. *Biogeochemistry* 28, pp. 33-54.

Abstract. Extensive areas of the eastern United States are being exposed to elevated levels of nitrogen in precipitation, with levels of inorganic N in wet deposition ranging from 5 to over 20 times preindustrial, background levels. This increase in N loading to the terrestrial system, coupled with changes in land use in coastal regions in particular, has dramatically increased the level of nutrient loading from watersheds to the point that coastal waters are today among the most intensely fertilized ecosystems on earth. Studies in upland, aggrading forests have generally found that precipitation N inputs are efficiently sequestered in forest biomass and soil organic matter. However, acidic soils, sandy, porous parent substrates, and chronic inputs of salt spray common to coastal watersheds may all reduce the potential for N sequestration by the terrestrial community.

We assessed the role of coastal forests in the long-term storage and retention of atmospherically-derived N in the watersheds of Waquoit Bay, MA, an increasingly eutrophic estuary on Cape Cod, by measuring precipitation inputs, storage, and lysimeter outputs below the rooting zone in a chronosequence of sites released from agriculture at different times. Calculated annual retention efficiencies were relatively low for an N-limited, aggrading forest (40–62%), and leaching losses did not vary with site age from young pine stands to mature beech forests. Nearly all nitrogen input was retained during summer months except in months with very high rainfall events. Nitrogen was released during the dormant-season in proportion to water flux through the forest floor. The composition of lysimeter output was 76% DON, 11% NO_3^-, and 13% NH_4^+. Total water flux and infiltration appear to be more important determinants of N retention in this sandy, coastal site than in more upland forest ecosystems; sandy systems may inherently have a low N retention efficiency.

Nowicki, B.L., Requintina, E., VanKeuren, D, and J. Portnoy. 1999. The role of sediment denitrification in reducing groundwater-derived nitrate inputs to the Nauset Marsh estuary, Cape Cod, Massachusetts. *Estuaries* 22(2A), pp. 245-259.

- Mixed use, coastal watershed
- Nauset marsh, Cape Cod, MA.
- Field/lab study
- Reports temperature, sediment organic content, denitrification rates in-situ and in sediment cores, groundwater nitrate concentration, porewater salinity, O2, dissolved N2, groundwater flow rates

Annotation:

Study examines denitrification and a variety of environmental variables in a Massachusetts coastal estuary. Results show denitrification does not contribute substantially to the direct loss of nitrate from incoming groundwater at Nauset Marsh estuary. In-situ denitrification rates were generally equal to or lower than rates measured in sediment cores, where denitrification was supported only by remineralized nitrate. Denitrification rates were similarly low in both surface sediments and those down to 1 m depth, suggesting no depth effect.

Implications:

- Nitrogen loss through denitrification is low in sandy coastal sediments on Cape Cod, but there may be potential for enhancing the process via reducing groundwater flow rate and/or increasing sediment organic matter

Weiskel P.K. and B.L. Howes. 1992. Differential transport of sewage-derived nitrogen and phosphorus through a coastal watershed. *Environmental Science and Technology* 26(2), pp. 352-360.

- Coastal watershed
- Indian Heights sub basin adjacent to Buttermilk Bay in Buzzards Bay, southeastern MA
- Field study
- Measured nitrate, nitrite, ammonium, total dissolved N, phosphate

Abstract not available in electronic format.

Annotation:

Study examined transport of N and P in septic system effluent (4 septic systems) and in groundwater at various distances down-gradient. Overall DIN losses during near-field transport were found to be insignificant, while PO4 loss was about 60%. Rapid conversion of ammonia to nitrate was seen in near-field groundwater (about 70% of ammonia was converted to nitrate in the initial meters of groundwater transport). At greater distances (10-100m) over 99% of dissolved N occurred as nitrate, phosphate concentrations were reduced to background levels, and N/P ratios exceeded 2500/1.

8.0 CONSTRUCTED WETLANDS

Allen, W.C., Hook, P.B., Biederman, J.A., and O.R. Stein. 2002. Temperature and Wetland Plant Species Effects on Wastewater Treatment and Root Zone Oxidation. *Journal of Environmental Quality* 31, pp. 1010–1016.

Abstract:

Constructed wetlands are widely used for wastewater treatment, but there is little information on processes affecting their performance in cold climates, effects of plants on seasonal performance, or plant selection for cold regions. We evaluated the effects of three plant species on seasonal removal of dissolved organic matter (OM) (measured by chemical oxygen demand and dissolved organic carbon) and root zone oxidation status (measured by redox potential [Eh] and sulfate [SO_2]) in subsurface-flow wetland (SSW) microcosms. A series of 20-d incubations of simulated wastewater was conducted during a 28-mo greenhouse study at temperatures from 4 to 24 degrees C. Presence and species of plants strongly affected seasonal differences in OM removal and root zone oxidation. All plants enhanced OM removal compared with unplanted controls, but plant effects and differences among species were much greater at 4 degrees C, during dormancy, than at 24C, during the growing season. Low temperatures were associated with decreased OM removal in unplanted controls and broadleaf cattail (Typha latifolia L.) microcosms and with increased removal in beaked sedge (Carex rostrata Stokes) and hardstem bulrush [Schoenoplectus acutus (Muhl. ex Bigelow) A. & D. Lo¨ ve var. acutus] microcosms. Differences in OM removal corresponded to species' apparent abilities to increase root zone oxygen supply. Sedge and bulrush significantly raised Eh values and $SO4^{2-}$ concentrations, particularly at 4 degrees C. These results add to evidence that SSWs can be effective in cold climates and suggest that plant species selection may be especially important to optimizing SSW performance in cold climates.

Axler, R, McCarthy, B. and J. Henneck. 2004. NERCC Individual Alternative Wastewater Treatment Systems: Pollutant Removal in 2003 and Long-term Performance. Northeast Regional Correctional Center, St. Louis County, Duluth, Minnesota. NRRI Technical Report NRRI/TR-2004/28. Natural Resources Research Institute University of Minnesota-Duluth. 5013 Miller Trunk Highway, Duluth, MN 55811

- Constructed wetlands or septic systems
- Duluth, Minnesota
- Field experiment
- Reports flow rate, DO, conductivity, temperature, BOD, TSS, TP, TN, NH_4-N, NO_3-N, Fecals

Abstract:

Near 500,000 Minnesota residences, commercial establishments and resorts rely on the use of onsite wastewater treatment systems to treat generated wastewater from these facilities. The need for effective onsite wastewater treatment systems in the state is growing to service new developments and to upgrade outdated on site sewage treatment systems (a.k.a. septic systems) with modern individual, shared, cluster or small community wastewater treatment systems. In 1995, a research site was established in northern Minnesota at the Northeast Regional Correction Center (NERCC) near Duluth, Minnesota, to design, construct, operate and monitor the performance of a variety of onsite wastewater treatment systems for use in the cold climate of Minnesota. The purpose of the research facility was to test the effectiveness of several onsite wastewater treatment technologies in removing organic matter, solids, pathogens, and nutrients at the same location using the same wastewater under identical climatic conditions. This phase of the study reports upon system performance during the 8th year of operating the facility (2003) after a 1 year

monitoring hiatus due to a funding shortfall. Performance results were obtained throughout the year for: replicated, in-ground single pass peat filters, modular peat filters using both Irish and a Minnesota peat, replicated, in-ground single pass sand filters, replicated subsurface flow constructed wetlands, and a recirculating textile filter with shallow infiltration trenches. Results for 2003 were tabulated in comparison to results from previous years. In addition, all of the data for these systems from all years of operation is summarized and tabulated. Additional discussion regarding operation and maintenance issues is also included.

Annotation:

As noted in abstract, this study involved monitoring and reporting on long-term performance of a variety of systems designed to treat wastewater. Performance results were obtained for a variety of sand and peat filters as well as constructed wetlands. Influent and effluent water monitoring data included TN, NH_4-N, and NO_3-N. Annual mean, median and range of N removal were given, along with monthly monitoring data. In-ground sand and peat filters showed high annual N removal (41-55% removal), while the constructed wetlands were somewhat less effective on an annual basis (15-20% removal). The report also notes a number of challenges associated with the wetland. In particular it was out of operation due to freezing during the coldest part of the winter.

Axler, R., Henneck , J. and B. McCarthy. 2001. Residential subsurface flow treatment wetlands in northern Minnesota. *Water Science and Technology* 44(11-12), pp. 345-352.

Abstract:

Approximately 30% of Minnesotans use on-site systems (~500,000 residences) and >50% are failing or non-compliant with regulations due to restrictive soils and site conditions. Many sites occur near lakes and streams creating health hazards and deteriorating water quality. SSF CWs have been evaluated year-round at two northern sites since 1995. The NERCC CWs simulate single homes and the Grand Lake demonstration CW treats STE from a cluster of 9 lakeshore homes. S ystems were generally able to achieve design criteria of 25 mgTSS/L and 30 $mgBOD_5$/L and the NERCC CWs required only 0.3m of unsaturated soil to achieve consistent disinfection to <200 fecals/100 mL year round. Seeding experiments with Salmonella indicated removal efficiencies of 99.8% in summer and 95% in winter. High strength (~300 mgBOD/L, 95 mgTN/L) influent at NERCC probably limited system performance, particularly N-removal (mass) which was ~42% in summer and 20% in winter. The data indicate CW's are a viable, year-round treatment option for homeowners in terms of performance, ease of operation, and cost but require additional maintenance related to inconsistent vegetation growth, winter insulation, and meeting concentration-based regulatory standards since they were seasonally and annually variable due to rain events, partial freezing, spring snowmelt, and summer evapotranspiration.

Crumpton, W.G., Isenhart, T.M., and S.W. Fisher. 1993. Fate of non-point source nitrate loads in freshwater wetlands: results from experimental wetland mesocosms. Ch. 29 in Constructed Wetlands for Water Quality Improvement. GA Moshiri, ed. Lewis Publishers.

- Constructed wetland
- Iowa State University
- Mesocosm experiment
- Reports general findings on nitrogen removal but not raw data

Abstract not available in electronic format.

Annotation:

Mesocosm studies were used to assess the capacity of freshwater wetlands to transform nitrate. Even under highly aerobic conditions, nitrate concentrations declined rapidly in water overlying wetland sediments in all experiments. When mesocosms with residence times of about a week were loaded with 3-15 mg/L of nitrate nitrogen, percent retention for nitrate exceeded 80%. The authors suggest nitrate loss rates can be modeled based on factors controlling the rate of nitrate flux to anaerobic sites, where denitrification takes place. This is consistent with other models that suggest that, in the presence of high nitrate loads, denitrification rates are controlled by the NO_3^- concentration in the overlying water and the effective length of the diffusion path between the overlying water and the primary site of denitrification in underlying anaerobic sediments.

David, R.L. and T.E. Conway. 1997. Nitrification and denitrification at the Iselin marsh/pond/meadow facility. Chapter 37cin Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. DA Hammer, Editor.

Abstract not available in electronic format.

Dornbush, J.N. 1993. Constructed waterwater wetlands: the answer in South Dakota's challenging environment. Ch. 63 in Constructed Wetlands for Water Quality Improvement. GA Moshiri, Ed.

Abstract not available in electronic format.

EPA. NADB (North American Treatment Wetland Database). Electronic database created by R. Knight, R Ruble, R Kadlec and S Reed for USEPA; online at http://firehole.humboldt.edu/wetland/twdb.html. And copies available from Don Brown, USEPA pp. 513-569-7630

- Constructed wetlands
- Throughout the US
- Electronic database
- Reports summary data from a variety of treatment wetland case studies

Abstract not available in electronic format

Annotation:

The treatment wetland database (TWDB) contains system descriptions and performance data for a large number of pilot, and full-scale wetland systems treating a variety of sources, including municipal wastewater, stormwater runoff, industrial wastewater, and agricultural runoff. The database contains the bulk of the entries in the revised EPA sponsored North American Database (NADB Version 2), and data from many additional treatment wetlands. While the emphasis is on constructed wetlands, natural wetlands are also included in the database.

EPA. 1999. Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment. EPA pp. 832-S-99-002, Office of Water.

- Constructed wetlands
- Throughout the US
- Electronic database
- Reports summary data from a variety of treatment wetland case studies

Abstract:

Free water surface wetlands have been engineered for water quality treatment in the United States since the early 1970s. Design information and operational performance data for these systems have been accumulating since that time and has led to the rapid development of a growing collection of literature. A number of efforts have been undertaken to summarize information from diverse data sources into a collection of performance descriptions. The most complete effort to date was the development of the North American Constructed Wetland Database (NADB) funded by the U.S. Environmental Protection Agency (EPA) (Knight et al. September 1993, NADB 1993, Brown and Waterman 1994).

The next step in assessing the performance of FWS treatment wetlands was to compile the assembled data into a summary of the state of knowledge. This technology assessment report describes the current understanding of processes and the performance of FWS treatment wetlands. In addition, areas of inadequate understanding are identified. The findings of this technology assessment will be incorporated into an update (in progress) of the U.S. Environmental Protection Agency's (EPA) FWS constructed wetland design manual (EPA 1988a) and the Water Environment Federation (WEF) Manual of Practice on Natural Systems (WEF, 1999), currently in preparation. Further, in the time period since the data analysis was performed for this assessment, many additional treatment wetland systems have become operational. Some of these systems have operation and performance data that are currently being used by researchers at Humboldt State University to update and provide a web-based version of the NADB by the end of 2000.

Annotation:

This report focuses on free water surface (FWS) wetlands, and gives a historical development of the technology, design issues, processes of importance (nutrient attenuation, provision of wildlife habitat), performance criteria, planning and design considerations, and recommendations on the design and use of a database for FWS wetlands. The report compares the performance of constructed wetlands with natural ones. It is noted that natural and constructed FWS wetlands function similarly, but there are some important differences. These differences are largely structural. Natural wetlands are more likely to have a forested plant community and to include a well-developed organic soil component than constructed wetlands. Natural wetlands are more likely to be subject to variable inflows and water depths and have more stagnant water zones outside the primary flow path that can reduce treatment efficiency. Also, hydraulic efficiency, the ability to utilize the entire wetland area in the process of water treatment, can be more nearly optimized in constructed wetlands than in most natural wetlands. The implication for this analysis is that changing the water flow regime in a wetland such that hydraulic efficiency is increased would enhance nitrogen uptake by natural wetlands.

EPA. 1999. Treatment Wetland Habitat and Wildlife Use Assessment and North American Treatment Wetland Database (NADB) Version 2. EPA 832-S-99-001. Prepared by CH_2M Hill.

- Constructed wetlands
- Throughout the US
- Electronic database
- Reports summary data from a variety of treatment wetland case studies

Abstract:

Natural and constructed wetlands are being used throughout North America and the world to improve the quality of a broad variety of wastewater types. Incidental to this water quality function, most of these wetlands have been observed to attract significant wildlife populations. In some cases these treatment wetlands also are available to humans for nature study and other forms of recreation.

Little effort has been made to collect or organize published and unpublished information concerning the wildlife habitat functions of treatment wetlands. New treatment wetland systems are being designed with very little guidance on attracting wildlife, or with guidance on whether such habitat creation is even compatible with the goal of protecting wetland biota. While it is generally conceded that treatment wetlands provide habitat for wildlife, the amount and quality of that habitat has not been widely recorded. Moreover, the potential for this habitat to threaten the health of wildlife attracted to treatment wetlands has been raised, but the documented occurrence of undesirable side effects has not been reviewed. There are few definitive studies of habitat values or of ecological impacts in treatment wetlands--and when they do exist, they are not generally available.

This report is one output from the United States Environmental Protection Agency’s (U.S. EPA's) Environmental Technology Initiative (ETI) Treatment Wetland Project. T his project is concerned with developing information and guidance to facilitate treatment wetland projects that provide multiple environmental benefits. The potential benefits of treatment wetlands include cost-effective improvement of water quality, creation of wildlife habitat, and enhancement of the public’s understanding and appreciation of wetlands. While other efforts within the ETI Treatment Wetland Project deal with the potential of treatment wetlands to improve water quality and with policy and permitting considerations, this report focuses on summarizing what is known about these systems in terms of their environmental effects and how they are used by the public.

The ETI Treatment Wetland Project has updated the North American Treatment Wetland Database (NADB Version [v.] 1.0) to include information on wildlife and their habitats and on issues related to wildlife hazards. This report summarizes the information in the updated database (NADB v.2.0), which is designed to store and analyze quantitative and qualitative data concerning the ecological measures that describe wetland plant communities; animal populations; concentrations of trace metals and organics in water,

sediments, and tissues in treatment wetlands; effects of wetlands on toxicity; and human use data from these systems.

Fleischer S., Gustofson, A., Joelsson, A., Pansar J. and L. Stibe. Nitrogen removal in created ponds. *Ambio* 23(6), pp. 349-357.

- Created wetland
- Swedish west coast
- Field study
- Reports chemical oxygen demand, total N, total P, pH, alkalinitiy, conductivity, and denitrification

Abstract not available in electronic format.

Annotation:

This study developed nitrogen budgets and estimates of nitrogen retention in five ponds in Sweden. Nitrogen retention was estimated for 1991-1993. Annual nitrogen removal per unit area varied by two orders of magnitude between the different ponds studied. Highest removal was observed in ponds with the highest N loading rates, but N removal efficiency didn't correlate well with N loading rates.

Geiger, S. 1993. Nitrogen and phosphorus reduction in secondary effluent using a 15-acre, multiple-celled reed canarygrass (*Phalaris arundinacea*) wetland. Ch. 33 in Constructed Wetlands for Water Quality Improvement. G. Moshiri, Ed.

Abstract not available in electronic format.

Gersberg, R.M., Elkins, B.V., and C.R. Goldman. 1983. Nitrogen removal in artificial wetlands. *Water Research* 17(9), pp. 1009-1014.

Abstract:

This report describes investigations which have demonstrated the exceptional utility of artificial wetlands for the removal of nitrate from secondary wastewater effluents at relatively high application rates. The artificial wetlands (14 in number) were plastic-lined excavations containing emergent vegetation growing in gravel. Without supplemental additions of carbon, total nitrogen removal efficiency was low (~25%) in both vegetated and unvegetated beds. When methanol was added to supplement the carbon supply and stimulate bacterial denitrification, the removal efficiency was extremely high (95% removal of total nitrogen at a wastewater application rate of 16.8 cm day^{-1}). Since methanol is a relatively expensive form of carbon, we tested the feasibility of using plant biomass, mulched and applied to the surface of marsh beds, as an alternate source of carbon. At a wastewater application rate of 8.4 cm day^{-1}, the mean total nitrogen removal efficiency for the mulch-amended beds was 86%. When the application rate was higher (16.8 cm day^{-1}) the mean total nitrogen removal efficiency was lower, 60% in the mulch-amended beds. By using plant biomass as a substitute for methanol, the energy savings for a treatment facility serving a small community (3785 m^3 day^{-1} or 1 mgd) would amount to the equivalent of 731 day^{-1} of methanol. As the cost of fossil fuel increases, energy cost will become a predominant factor in the selection of small (0.5-5 mgd) wastewater treatment systems. However, in many cases where natural wetlands are either geographically unavailable or protected from wastewater discharge by environmental, legal, or aesthetic restraints, artificial wetlands offer a viable alternative for energy-effective treatment of municipal and agricultural wastewater effluents.

Annotation:

- Constructed wetland
- Santee, CA
- Field experiment
- Reports nitrogen removal efficiency, total N, total P, orthophosphate, and TSS

This paper reports nitrogen, suspended solids, and phosphorus removal by constructed wetlands both with and without mulch as an added carbon source. The carbon source is important in that denitrifying bacteria require a carbon source. Nutrient removal was highest in the mulch-amended beds during the first two months of the experiment, when vegetation was becoming established (during fall). Cutting and mulching the vegetation in place was found to be an effective method for adding a carbon source. The implication for this work is that it may be necessary to add a carbon source to certain wetlands where soil organic carbon is low in order to enhance denitrifying bacterial activity.

Green, M.B. and J. Upton. 1993. Reed Bed Treatment for Small Communities - UK Experience. Ch. 57 in Constructed Wetlands for Water Quality Improvement. GA Moshiri, Ed. CRC Press.

- Constructed wetland
- Little Stretton, UK
- Field study
- Reports BOD, suspended solids, NH_3-N, TON, ortho-Phosphate

Abstract: none available in electronic format.

Annotation:

This article reports on the performance of a constructed reed bed treatment system. The system was installed to replace a sewer dyke that was polluting a nearby river. A terraced series of 2m by 12m reed beds was planted with *Phragmites*. Influent and effluent water was tested for the parameters listed above. During the first two years of operation there was ponding and buildup of anaerobic material in certain areas. Improvement in inflow/outflow properties led to an improvement in nutrient and suspended solids retention. Annual averages are given for the whole system, and a week's worth of data is given at the inlet, outlet, and three intermediate stations. The authors note that 1) effluent water has consistently been of high quality in terms of BOD; 2) significant nitrification takes place in the system; 3) nitrate from inputs and that produced by nitrification is removed via denitrification. The reed bed method was adopted by Severn Trent Water Ltd as a preferred option for secondary treatment for populations of up to 50 and tertiary treatment for populations up to 1500.

Hansson, L.A., Bronmark, C., Nilsson, P. Anders and K. Abjornsson. 2005. Conflicting demands on wetland ecosystem services: nutrient retention, biodiversity, or both? *Freshwater Biology* 5, pp. 705–714.

- Constructed wetlands
- Southern Sweden
- Field study
- Data on phosphorus, nitrogen, biota (species numbers, richness for macrophytes, birds, benthic invertebrates, and fish) and physical wetland features (age, size, depth, shoreline complexity)

Abstract:

1. Wetland ecosystems may, besides having considerable economical value, increase landscape biodiversity and function as traps for nutrients from land to freshwater-and marine systems. As a result of these

features, wetlands are nowadays often protected and restored, and many countries have even initiated wetland construction programmes.

2. In the present study, we aim at increasing the knowledge on how to improve the design of a wetland with respect to both biodiversity and nutrient retention, by analysing physical, chemical and biological features of a large set of constructed wetlands.

3. Our results show that a combination of the wetland features, namely shallow depth, large surface area and high shoreline complexity are likely to provide a high biodiversity of birds, benthic invertebrates and macrophytes and to have high nitrogen retention, whereas a small, deep wetland is likely to be more efficient in phosphorus retention, but less valuable in terms of biodiversity.

4. Hence, among the features used to design new wetlands, area, depth and shoreline complexity have fundamental, and sometimes conflicting, effects on nutrient retention and biodiversity. This means that there are, within limits, possibilities to direct the ecosystem function of a specific wetland in desired directions.

Annotation:

Found both nitrogen retention and biodiversity to be enhanced in wetlands of shallow depth, large surface area and high shoreline complexity. Phosphorus retention was enhanced in small, deep wetlands.

Implications:

- Shallow wetlands with large surface area and high shoreline complexity are likely to be most effective in nitrogen retention
- Biological diversity is enhanced by the same features so wetlands designed for nitrogen retention may also increase biodiversity

Healy, M. and A.M. Cauley. 2002. Nutrient processing capacity of a constructed wetland in Western Ireland. *Journal of Environmental Quality* 31, pp. 1731-1739.

Abstract:

In Ireland, constructed wetland systems are increasingly being used to perform tertiary treatment on municipal waste effluent from small towns and villages located in areas whose receiving waters are deemed sensitive. The bedrock formation in the west of Ireland is primarily karst limestone and where the overburden–soil cover is very shallow, such waters are highly sensitive to pollution sources, as little or no natural attenuation and/or treatment will occur. Constructed wetland technology has been seen to offer a relatively low-cost alternative to the more conventional tertiary treatment technologies, particularly when dealing with low population numbers in small rural communities. This paper examines the waste treatment performance, in terms of nutrient (P and N) reduction, of a recently constructed surface-flow wetland system at Williamstown, County Galway, Ireland. Performance evaluation is based on more than two years of water quality and hydrological monitoring data. The N and P mass balances for the wetland indicate that the average percentage reduction over the two-year study period is 51% for total N and 13% for total P. The primary treatment process in the wetland system for suspended solids (between 84 and 90% reduction), biological oxygen demand (BOD) (on average, 49% reduction), N, and P is the physical settlement of the particulates. However, the formation of algal bloom during the growing season reduces the efficiency of the total P removal.

Hey, D.L., Kenimer, A.L., and K.R. Barrett. 1994. Water quality improvement by four experimental wetlands. *Ecological Engineering* 3, pp. 381-394

- Constructed wetland

- Des Plaines River Wetlands Demonstration Project near Chicago
- Field study
- Measured TSS, NO3-N, Total P

Abstract:

Four constructed, experimental wetlands at the Des Plaines River Wetlands Demonstration Project near Chicago, Illinois, USA, were studied during the 1990 and 1991 growing seasons, to evaluate certain water quality functions. The wetlands, ranging in size from 2 to 3.5 hectares with a maximum depth around 1.5 m, were supplied with water from the nearby Des Plaines River. Concentrations of total suspended solids, volatile suspended solids, nitrate-nitrogen, and total phosphorus, measured at the inlet and outlet of each wetland, were consistently lower at the outlets. Based on constituent mass balances for each wetland, trap efficiencies (percent removal) ranged from 76 to 99% for total suspended solids, from 39 to 99% for nitrate-nitrogen, and from 52 to 99% for total phosphorus. Although the wetlands were subjected to different hydraulic loading rates, their effluent water quality was similar. Also, although constituent concentrations of the influent were often quite high and varied significantly with respect to time, the outlet concentrations remained low and steady. High removal rates and low variability in effluent with respect to both inlet concentration and hydraulic loading rate suggest that the wetlands were not stressed, but rather, are capable of treating substantially greater quantities of water than were applied during 1990 and 1991.

Annotation:

Four wetlands (2-3.5 ha in size, max depth 1.5m) were supplied with water from the Des Plaines River. Total suspended solids (TSS), volatile suspended solids (VSS), nitrate-nitrogen (NO_3-N), and total phosphorous (TP) were measured at the inlet and outlets of each wetland. Percent removal ranged from 76-99% for TSS, 39-99% NO_3-N, and 52-99% TP. Although the wetlands were subjected to different hydraulic loading rates, their effluent water quality was similar. Although influent was variable and often had high concentrations the outlet concentrations remained low and steady, suggesting these wetlands have the capacity to treat substantially greater quantities of water than were applied during this trial period.

Hey, D.L., Kostel, J.A., Hurter, A.P., and R.H. Kadlec. 2005. Nutrient farming and traditional removal: An economic comparison. Water Environment Research Foundation (WERF) 03-WSM-6CO

- Constructed wetland
- Des Plaines River Wetlands Demonstration Project near Chicago
- Bio-economic analysis of treatment wetlands vs. sewage treatment plant upgrades for N removal
- Based on data from various experiments done by the authors and others

Abstract not available electronically

Annotation:

The study evaluates conventional wastewater treatment vs. nutrient "farming" in constructed/managed wetlands and estimates costs of each. Proposes nutrient farming as a viable alternative to upgrading seven water treatment plants around Chicago. A model of free surface wetlands was developed based on information in Kadlec and Knight, 1996, Treatment Wetlands, CRC Lewis Publishers.

Nitrogen removal rates were estimated. The rate constant for nitrate removal was a function of temperature. For TN the difference between influent and outlet concentrations was calculated as removal of oxidized N plus a 1.5 mg/L gain in organic N.

The authors note the importance of emergent plants in both promoting settling of suspended sediment and providing surface area for microbial biofilm growth. Wetland area was determined based on winter removal capacity. The authors propose that excess nutrient removal capacity in summer could be used as a nitrogen removal banking scheme wherein nutrient removal credits are sold in a manner similar to pollution credits.

Hofmann, K. 1997. The role of plants in subsurface flow constructed wetlands. Ch. 17, pages 183-196 in Ecological Engineering for Wastewater Treatment. C. Etnier and B Guterstam, editors.2nd Edition. CRC Press.

Abstract not available electronically

Kadlec, R.H., Axler, R., McCarthy, B., and J. Henneck. 2003. Subsurface treatment wetlands in the cold climate of Minnesota. Ch. 2 in Constructed Wetlands for Wastewater Treatment in Cold Climates U Mander and PD Jenssen, eds. WIT Press, Southampton, U.K. and Boston, U.S.

Abstract not available electronically

Kadlec, R.H., Tanner, C.C., Hally, V.M., and M.M. Gibbs. 2005. Nitrogen spiraling in subsurface-flow constructed wetlands: implications for treatment response. *Ecological Engineering* 25, pp. 365-381.

Abstract:

Nitrogen processing in treatment wetlands was investigated by use of the stable isotope ^{15}N introduced as ammonium. Two small field-scale, gravel-bed wetlands with horizontal subsurface-flow (SSF) received primary meat processing water. Four SSF cascade mesocosms, each comprising five tanks in series, received primary meat processing water, primary dairy water, secondary dairy water or aerated secondary dairy water. The mesocosms and one of the field-scale wetland contained well-established bulrushes (*Schoenoplectus tabernaemontani*), and the other field-scale wetland remained unvegetated. The systems were operated at steady inflows, with a nominal detention times of 4–5 days. The incoming ammonium nitrogen ranged from 18.5 to 177 g m^{-3}, and removals ranged from 15 to 90% for the various feed waters.

Each system was dosed with a single pulse of ^{15}N ammonium mixed into the feed wastewater, and the fate and transport of the isotopic nitrogen were determined. The ^{15}N pulses took 120 days to clear the heavily loaded field-scale wetlands. During this period small reductions in ^{15}N were attributable to nitrification/denitrification, and a larger reduction due to plant uptake. Mesocosm tests ran for 24 days, during which only 1–16% of the tracer exited with water, increasing with N loading. Very little tracer gas emission was found (~1%). The majority of the tracer was found in plants (6–48%) and sediments (28–37%). These results indicated a rapid absorption of ammonium into a large sediment storage pool, of which only a small proportion was denitrified during the period of the experiment. Plant uptake claimed a fraction of the ammonium, determined mainly by the plants requirement for growth rather than the magnitude of the nitrogen supply. A rapid return of ammonium to the water was also found, so that movement of ^{15}N through the wetland mesocosms was comprised of a spiral of uptake and release along the flow path. A two compartment model was found to reasonably represent the isotope progress through the wetlands. First order exchanges and removals were employed in dynamic mass balances on water and solids. It is concluded that interpretation of nitrogen dynamics in wetlands must include the nitrogen spiral through the wetland, as well as plant uptake. This greatly increases the N residence time in treatment wetlands relative to the hydraulic detention time, resulting in long delays of treatment system response to changes in N loading and attenuation of short-term fluctuations in loading.

Kadlec, R.H. and R.L. Knight. 1996. Wetland Treatment System Inventory. Chapter 26 in Treatment Wetlands. Lewis Publishers New York.

- Constructed wetlands
- Locations throughout North America
- Database/desktop study
- Presents summary data from a variety of constructed wetlands used in treatment systems

Abstract not available electronically:

Annotation:

The authors developed a database to summarize existing information on engineered wetalnds, and to provide a quantitative basis for planning and design of new systems. The database was compiled for and sponsored by EPA. The list of wetlands includes 176 wetland treatment sites with 203 separate treatment systems. Summary data on these systems includes geographical location, wastewater source, wetland area, vegetation, flow rates, operating costs, and long-term, average performance data. Performance data includes influent and effluent for the following: BOD, TSS, NH4, total N, and total P. Overall, total nitrogen retention in these treatment wetlands averages 53%, NH4-N removal is about 52% and NO2+NO3 removal is about 62%. This review also describes operational and system design information for Danish reed bed wetland treatment systems.

Knight, R.L., Ruble, R.W., Kadlec ,R.H. and S. Reed. 1993. Wetlands for Wastewater Treatment: Performance Database. Ch. 4 in Constructed Wetlands for Water Quality Improvement. GA Moshiri, Ed. Lewis Publishing Boca Raton.

Abstract not available electronically

Lund, L.J., Horne, A.J., and A.E. Williams. 2000. Estimating denitrification in a large constructed wetland using stable nitrogen isotope ratios. Ecological Engineering 14, pp. 67-76.

Abstract:

Nitrate losses and their relationships to nitrogen isotope fractionation were evaluated in a wetlands environment in southern California. This paper reports the first study to follow isotope ratio changes in a large natural system with extensive macrophyte growth. As NO_3 concentrations decreased during flow through the wetlands, progressive enrichment in $^{15}NO_3$ was found. This increase corresponded to an enrichment value of −2.5‰, a value much lower that those reported for laboratory studies of denitrification (−17 to −29‰), but closer to the range of enrichment factors attributed to denitrification in studies of groundwaters (−3.5 to −16‰). By considering a laboratory derived value of −17‰ as the enrichment factor strictly due to denitrification, 10–23% of the Prado losses could be attributed through isotope enrichment to denitrification. Other studies at Prado, using a mass balance approach which considered macrophyte growth, concluded that bacterial denitrification was the major loss mechanism (89–95%). A similar, but somewhat smaller discrepancy between estimates of denitrification was found in nearby wetlands with large shallow water bodies with dense phytoplankton growth but negligible macrophytes. These discrepancies suggest that enrichment or fractionation factors derived under laboratory conditions where all nitrogen losses are attributable to denitrification cannot be used directly as the denitrification end-member in field situations where organic matter decomposition and nitrogen recycling are occurring simultaneously or sequentially with denitrification. Further studies which consider entire growing and decomposition cycles in macrophyte-rich wetlands are needed to resolve the discrepancy in the various methods of estimating dentrification in natural wetlands.

Mayer, P.M., S.K. Reynolds, and T.J. Canfield. 2005. Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations. EPA 600/R-05/118. October 2005.

- Constructed wetland/buffer strips
- Various locations
- Review of published literature
- No new data provided

Annotation:

This review of literature on vegetative buffers evaluates nitrogen removal effectiveness among different buffer types and sizes. Nitrogen removal effectiveness was found to vary widely among the various types and sizes of areas studied. While some narrow buffers (1-15 m) removed significant proportions of nitrogen, narrow buffers actually contributed to nitrogen loads in riparian zones in some cases. Wider buffers (>50 M) more consistently removed significant portions of nitrogen entering a riparian zone. Buffers of various vegetation types were equally effective at removing nitrogen in the subsurface but not the surface flow. The general lack of vegetation type or buffer width effect on subsurface nitrogen removal suggests that soil type, watershed hydrology (e.g. soil saturation, groundwater flow paths, etc.) and subsurface biogeochemistry (organic carbon supply, high nitrate inputs) may be more important factors dictating nitrogen concentrations due to their influence on denitrification. State and Federal guidelines for buffer width generally were consistent with peer-reviewed literature, recommending or mandating buffers about 7-100m wide. Proper design and construction are critical to buffer effectiveness. To maintain maximum effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation, and stream incision. Restoring degraded riparian zones and stream channels may improve nitrogen removal capacity.

Mitsch, W.J., L. Zhang, C.J. Anderson, and A.E. Altor. 2005. Creating riverine wetlands: ecological succession, nutrient retention, and pulsing effects. Ecological Engineering 25:510-527.

- Constructed wetland
- Midwest
- Field experiment
- Data on nitrogen, phosphorus, plant species diversity, percent cover, soil color, soil organic matter, macrophyte productivity, phosphorus content

Successional patterns, water quality changes, and effects of hydrologic pulsing are documented for a whole-ecosystem experiment involving two created wetlands that have been subjected to continuous inflow of pumped river water for more than 10 years. At the beginning of the growing season in the first year of the experiment (1994), 2400 individuals representing 13 macrophyte species were introduced to one of the wetland basins. The other basin was an unplanted control. Patterns of succession are illustrated by macrophyte community diversity and net aboveground primary productivity, soil development, water quality changes, and nutrient retention for the two basins. The planted wetland continued to be more diverse in plant cover 10 years after planting and the unplanted wetland appeared to be more productive but more susceptible to stress. Soil color and organic content continued to change after wetland creation and wetlands had robust features of hydric soils within a few years of flooding. Organic matter content in surface soils in the wetlands increased by approximately 1% per 3-year period. Plant diversity and species differences led to some differences in the basins in macrophyte productivity, carbon sequestration, water quality changes and nutrient retention. The wetlands continued to retain nitrate–nitrogen and soluble reactive phosphorus 10 years after their creation. There are some signs that sediment and total phosphorus retention are diminishing after 10 years of river flow. Preliminary results from the beginnings of a flood pulsing experiment in the two basins in 2003–2004 are described for water quality, nutrient retention, aboveground productivity, and methane and nitrous oxide gaseous fluxes.

Annotation:

This paper reports ten years of data on wetland characteristics and nutrient retention in two constructed wetlands – one planted with macrophytes and one unplanted. Nitrate-N reduction through the wetlands averaged close to 35% by concentration and mass. Nitrate removal in the unplanted, naturally colonizing wetland were erratic, ranging from 20% in the first year to 40% the next. The planted, more diverse wetland had more consistent removal rates throughout the years, but still ranged from under 20% to almost 50%. Pulsing experiments (introduction of artificial floods by pumping in additional river water) led to nitrate removal rates over 40% - among the highest loss rates seen in the ten years of sampling.

Abstract:

Successional patterns, water quality changes, and effects of hydrologic pulsing are documented for a whole-ecosystem experiment involving two created wetlands that have been subjected to continuous inflow of pumped river water for more than 10 years. At the beginning of the growing season in the first year of the experiment (1994), 2400 individuals representing 13 macrophyte species were introduced to one of the wetland basins. The other basin was an unplanted control. Patterns of succession are illustrated by macrophyte community diversity and net aboveground primary productivity, soil development, water quality changes, and nutrient retention for the two basins. The planted wetland continued to be more diverse in plant cover 10 years after planting and the unplanted wetland appeared to be more productive but more susceptible to stress. Soil color and organic content continued to change after wetland creation and wetlands had robust features of hydric soils within a few years of flooding. Organic matter content in surface soils in the wetlands increased by approximately 1% per 3-year period. Plant diversity and species differences led to some differences in the basins in macrophyte productivity, carbon sequestration, water quality changes and nutrient retention. The wetlands continued to retain nitrate–nitrogen and soluble reactive phosphorus 10 years after their creation. There are some signs that sediment and total phosphorus retention are diminishing after 10 years of river flow. Preliminary results from the beginnings of a flood pulsing experiment in the two basins in 2003–2004 are described for water quality, nutrient retention, aboveground productivity, and methane and nitrous oxide gaseous fluxes.

Annotation:

This study showed that 1) wetlands can be successfully created if the appropriate hydrologic conditions are maintained; 2) wetland plant communities develop if hydrology is appropriate and plant propagules are available; 3) wetlands can be nutrient sinks for years if they are not overloaded with nutrients; 4) the addition of plants to enhance biodiversity can lead to a reduction in productivity of macrophytes and subsequent changes in food webs; 5) there are desirable aspects of both highly diverse and highly productive wetlands

Newman, J.M., Clausen, J.C. and J.A. Neafsey. 2000. Seasonal performance of a wetland constructed to process dairy milkhouse wastewater in Connecticut. *Ecological Engineering* 14, pp. 181–198.

Abstract:

Constructed wetlands are gaining increased attention for treatment of nonpoint sources of water pollution. Although constructed wetlands have been utilized for wastewater treatment in warm climates, their performance in cold climates has been questioned. A surface-flow wetland, designed to treat 2.65 $m^3 d^{-1}$ of milkhouse wastewater, was constructed on the University of Connecticut's Storrs campus in 1994. The purpose of the project was to determine the efficiency of the system in reducing nitrogen, phosphorus, five-day biochemical oxygen demand (BOD), total suspended solids (TSS), and fecal coliform bacteria (FC). The wetland was designed to process an estimated BOD5 loading rate of 7.3 g $m^{-2}d^{-1}$, which was less than half of the average actual loading rate. The overall percentage of mass retention was 94, 85, 68, 60 and 53% for TSS, BOD, total phosphorus, nitrate–nitrite and total Kjeldahl-nitrogen, respectively. Although the wetland became a net source of ammonia nitrogen (NH_3-N) following plant die back in fall 1994, NH_3-N outflow concentrations have gradually declined over time. Mass retention was significantly greater ($P < 0.05$) during the summer than during the winter for all variables except FC. Denitrification rates measured using the acetylene block method have shown denitrification to be a minor removal mechanism (< 1%) for nitrogen in this wetland. The mass balance indicated that settling and increased storage was the largest removal mechanism. The treatment of wastewater in this wetland did not meet design outflow concentration criteria, most likely due to BOD overloading.

Obarska-Pempkowiak, H. 1997. Seasonal variations in the efficiency of nutrient removal from domestic effluent in a quasi-natural field of reeds (Phragmites australis). Ch. 19, pages 207-216 in Ecological Engineering for Wastewater Treatment. 2nd Edition.

Abstract not available electronically

Peterson, S.B. and J.M.Teal. 1996. The role of plants in ecologically engineered wastewater treatment systems. Ecological Engineering 6:137-148.

- Constructed wetland
- New England
- Field experiment
- Presents data on

Abstract:

A Solar Aquatic System™ (SAS) septage treatment facility with aquaculture and constructed marsh components operated as a pilot facility from 1989 through 1992. The nitrogen loadings to the aquaculture subsystem were 15.6 gN m^{-2} day^{-1}. Sixty-eight percent of the nitrogen was removed, with 4% of the removal by vegetative uptake. The nitrogen loading to the marsh subsystem was 5.23 gN m^{-2} day^{-1}. Thirty-eight percent of the nitrogen was removed, with 1% of the removal by vegetative uptake. Although responsible for only a fraction of the nitrogen removal, the productivity of the plants in the SAS was comparable to that of plants in less heavily loaded wetland systems reported in the literature. The nitrogen content of plants in the SAS was higher than of plants in a heavily loaded system. Comparisons are made among three wetland systems with loadings ranging from 0.44 to 1.83 gN m^{-2} day^{-1} where up to 30% of the nitrogen was removed by the plants.

Annotation:

This study evaluated nitrogen removal in a constructed 'wetland' including an aquaculture unit and consstructed marshes. The nutrient load was higher than most constructed wetlands because the system treated concentrated septage rather than sewage. Removal of nitrogen by plants was a small fraction of the total N removal but plant productivity was similar to that of other constructed wetlands. Total N removal was a substantial fraction of N load to the system, with the bulk of the N removal occurring in the aquaculture system.

Phipps, R.G. and W.G. Crumpton. 1994. Factors affecting nitrogen loss in experimental wetlands with different hydrologic loads. *Ecological Engineering* 3, pp. 399-408.

- Constructed wetland
- Des Plaines River Wetlands Demonstration Project near Chicago
- Field study
- Measured ammonium, NO_3-N, Total N, Organic N, Total P

Abstract:

Constructed or restored wetlands have great potential for reducing nonpoint source contamination of surface and ground waters by agricultural chemical contaminants. The work reported here combines field and experimental studies of factors affecting nitrogen loss in the Des Plaines River Experimental Wetlands, northeastern Illinois, USA. These wetlands receive approximately 5–36 cm/week of pumped river water with significant but seasonally variable loads of nitrate and organic nitrogen. On an annual basis, the wetlands removed 78–95% of the nitrate and 54–75% of the total nitrogen received. At the low hydrologic loading rate, organic nitrogen exports approximately equalled imports. However at the higher hydrologic loading rate, the wetlands exported 22–31% more organic nitrogen than received. Seasonal variation in nitrate and organic nitrogen loads had significant effects on the effectiveness of the wetlands as sinks for total nitrogen. The wetlands were nitrogen sinks during periods of high nitrate loading and nitrogen sources during periods of low nitrate loading. Experimental studies demonstrated the effects of nitrate concentration, temperature, and location on rates of nitrate loss. Results suggest that nitrate loading rates might influence not only nitrate loss rates but also loss rate coefficients.

Annotation:

Constructed freshwater wetlands received about 5-36 cm/week of pumped river water with significant but seasonally variable loads of nitrate and organic N. On an annual basis, the wetlands removed 78-95% of the nitrate and 54-75% of the total N received. At the low hydrologic loading rate, organic N exports approximately equaled imports. But at the higher hydrologic loading rate the wetlands exported 22-31% more organic N than received. Microcosm tests (sediment core experiments) showed that temperature and nitrate loading rate affected N removal efficiency. Note: temperature effect was significant in just three of six microcosm experiments. The wetlands were nitrogen sinks during periods of high nitrate loading and nitrogen sources during periods of low nitrate loading.

Nitrate concentrations in water exiting the wetlands were consistently reduced relative to inlet concentrations. However, concentrations of organic N were frequently higher in water exiting the wetlands than in water entering. As a result, during periods of high nitrate load, when nitrate comprised most of the total N load, the wetlands were effective sinks for total N. In contrast, during periods of low nitrate loading in the summer, when organic N comprised most of the total N load, the wetlands were frequently sources for total N.

On an annual basis, all of the wetlands were sinks for nitrate, with high-flow wetlands removing 78-84% of the nitrate received and low-flow wetlands removing 95% of nitrate received. Evaporative loss of water in low-flow wetlands led to higher organic N concentrations in export water than inlet water at certain times.

Schipper, L.A. and M. Vojvodic´-Vukovic. 2000. Nitrate removal from groundwater and denitrification rates in a porous treatment wall amended with sawdust. *Ecological Engineering* 14, pp. 269–278.

- Constructed wetland
- Cambridge, North Island, New Zealand
- Field and lab experiments
- Reports NO_3 in groundwater and denitrification enzyme activity, groundwater flow rates, and nitrate removal

Abstract:

Porous treatment walls are increasingly used for remediating contaminated groundwater. These walls are constructed below the water table and perpendicular to the groundwater flow. Successful nitrate removal from groundwater has been demonstrated in porous walls amended with sawdust but the mechanism responsible has not been identified. The objective was to determine whether denitrification rates in such a wall were high enough to account for observed nitrate removal. During a year-long field trial, the rate of nitrate removal from groundwater was measured as it passed through a 1.5 m wide wall. Concurrently, denitrification rates were measured in samples taken from the wall using an acetylene-inhibition technique. Denitrification rates (0.6–18.1 ng $cm^{-3}h^{-1}$) were generally high enough to account for the nitrate losses in groundwater (0.8–12.8 ng N $cm^{-3}h^{-1}$), except on one occasion, when nitrate loss in groundwater was greater than 50 ng N $cm^{-3}h^{-1}$. When the water table dropped below the wall, nitrate inputs were decreased, and there were concurrent declines in denitrification rates. Rates subsequently increased once the water table rose. Laboratory incubations also demonstrated that denitrification was highly responsive to nitrate inputs. Denitrification rates increased by an order of magnitude within 7 h of nitrate addition. This treatment wall has removed nitrate from groundwater for more than 2.5 years and denitrification rates were high enough to account for nitrate removal.

Annotation:

Evaluated nitrate loss and denitrification activity in a porous groundwater treatment wall with sawdust. Since the mechanism of nitrogen loss with these systems hasn't been well identified, the study aimed at evaluating whether denitrification could account for all observed nitrate loss. Results showed denitrification within the wall was generally sufficient to account for losses of nitrate from groundwater passing through the wall.

Implication: denitrification is the major process underlying nitrate loss in this type of system.

Spiels, D.J. and W.J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: a comparison of low- and high-nutrient riverine systems. *Ecological Engineering* 14, pp. 77–91.

- Constructed wetland
- Central Ohio, USA
- Field experiments
- Reports nutrient removal

Abstract:

We compared the nitrate removal efficiency of two constructed wetlands receiving ambient river water to one constructed municipal wastewater treatment wetland over the same 2-year period in central Ohio, USA. The wastewater wetland represents a high-nutrient system, with an average nitrate plus nitrite load of 12.3 kg N $ha^{-1} day^{-1}$ and an average nitrate and nitrite inflow concentration of 12.5 mg N l^{-1}. The riverine wetland loadings and concentrations were approximately 60% lower (4.6–4.7 kg N $ha^{-1} day^{-1}$ and 4.6 mg N l^{-1}). Percent nitrate removal by mass ranged from 29% in the wastewater wetland to 37–40% in the riverine wetlands, although differences in retention varied widely by season and were not statistically significant among the wetlands. Retention efficiency was considerably lower in all three wetlands during floods; nitrate outflow was as much as 400% greater than inflow during some flood events. We developed a simple Vollenweider-type model of nitrate retention based on seasonal temperature, hydraulic loading, and nitrate loading. The model is general enough to be useful in describing nitrate retention in both high and low-loaded wetlands and was calibrated and validated with extensive field data. The model was used to predict wetland nitrate removal efficiency as the hydrologic and nutrient conditions change. The ability to make such predictions could be valuable in the design, construction, and management of wetlands for nutrient removal.

Annotation:

This study compared nutrient removal efficiency in wetlands with high- vs. low-nutrient loads, both annually in seasonally. Annual rates of nitrogen removal ranged from about 30-40% in both systems, with highest removal rates in summer (about 50-60%) and lowest (around 10%) in spring. Springtime lows in nitrogen retention were related to periodic flooding. The systems tested here showed relatively low nitrate removal compared to other studies. The authors note this may be related to the young age of the wetland, or to insufficient organic matter, although the periodic flood-induced nitrate export influenced the results.

Steiner G.R. and D.W. Combs. 1993. Small constructed wetlands systems for domestic wastewater treatment and their performance. Ch. 54 in <u>Constructed Wetlands for Water Quality Improvement</u>. GA Moshiri, Ed. CRC Press.

Abstract not available electronically

Stengel, E. and R. Schultz-Hock. 1989. Denitrification in artificial wetlands. Ch. 37d, pages 485-492 in Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. DA Hammer, Editor. Lewis Publishers.

Abstract not available electronically

Sunblad, K. and Hans-B. Wittgren. 1997. Wastewater nutrient removal and recovery in an infiltration wetland. Ch. 18, pages 197-214 in Ecological Engineering for Wastewater Treatment. 2nd Edition. C. Etnier and B Guterstam. CRC Press.

Abstract not available electronically

Tittleton, R.P., Howell, F.G. and R.P. Reaves. 1993. Performance of a constructed marsh in the tertiary treatment of bleach Kraft pulp mill effluent: results of a 2-year pilot project. Ch. 46 in Constructed Wetlands for Water Quality Improvement. GA Moshiri, Ed. Lewis Publishers Boca Raton.

Abstract not available electronically

Toet, S., Van Logtestijn, R.S.P., Kampf, R., Schreijer, M., and J.T.A. Verhoeven. 2005. The effect of hydraulic retention time on the removal of pollutants from sewage treatment plan effluent in a surface-flow wetland system. *Wetlands* 25(2), pp. 375–391.

Abstract:

We evaluated the effect of four hydraulic retention times (HRT, 0.3, 0.8, 2.3, and 9.3 days) on pollutant removal in a surface-flow wetland system for polishing tertiary effluent from a sewage treatment plant (STP). The removal efficiency of pollutants at these HRTs was based on mass budgets of the water inputs and outputs in parallel ditches, which together with a presettling basin, made up the wetland system. Fecal coliform and N-removal efficiencies in the ditches were enhanced by increasing the HRT, with only little removal of fecal coliforms during spring-summer at a HRT of 0.3 days. A HRT of 4 days turned out to be required to meet the desired bathing water standard for fecal coliforms (103 cfu 100 ml21) and the future standard of ammonium (1 mg N l21) all year. An annual N-removal efficiency of approximately 45% can be accomplished in the ditches at this HRT, corresponding to an annual N mass loading rate of 150 g N m22 yr21. A nnual P removal was not improved by increasing the HRT even up to 9.3 days, largely because of the still high P mass loading rate (14 g P m22 yr21) in combination with relatively low P input concentrations. Substantial P removal can probably only be achieved at HRTs longer than 15 days, which will not be feasible for the situation investigated because of the large land area that would be required to reach such long HRTs. The future P standard (1 mg P l21) can therefore only be met by additional chemical P removal. In a densely populated country such as the Netherlands, adequate polishing of tertiary STP effluent in surface-flow wetlands with similar goals as for this wetland is restricted to small and medium-sized STPs. The simultaneous use of these treatment wetlands for other functions, such as nature conservation, recreation, and flood control, however, would permit the use of relatively larger land areas.

9.0 MODELED WETLANDS

Alexander, R.B., Johnes, P.B., Boyer, E.W. and R.A. Smith. 2002. A comparison of models for estimating the riverine export of nitrogen from large watersheds. *Biogeochemistry* 57/58, pp. 295-339.

Abstract:

We evaluated the accuracy of six watershed models of nitrogen export in streams (kg km^{2} yr^{-1}) developed for use in large watersheds and representing various empirical and quasi-empirical approaches described in the literature. These models differ in their methods of calibration and have varying levels of spatial resolution and process complexity, which potentially affect the accuracy (bias and precision) of the model predictions of nitrogen export and source contributions to export. Using stream monitoring data and detailed estimates of the natural and cultural sources of nitrogen for 16 watersheds in the northeastern United States (drainage sizes = 475 to 70,000 km^{2}), we assessed the accuracy of the model predictions of total nitrogen and nitrate-nitrogen export. The model validation included the use of an error modeling technique to identify biases caused by model deficiencies in quantifying nitrogen sources and biogeochemical processes affecting the transport of nitrogen in watersheds. Most models predicted stream nitrogen export to within 50% of the measured export in a majority of the watersheds. Prediction errors were negatively correlated with cultivated land area, indicating that the watershed models tended to over predict export in less agricultural and more forested watersheds and under predict in more agricultural basins. The magnitude of these biases differed appreciably among the models. Those models having more detailed descriptions of nitrogen sources, land and water attenuation of nitrogen, and water flow paths were found to have considerably lower bias and higher precision in their predictions of nitrogen export.

Arheimer B. and H.B. Wittgren. 1994. Modelling the effects of wetlands on regional nitrogen transport. *Ambio* 23(6), pp. 378-386.

Abstract not available electronically

Annotation:

- Model based on constructed wetlands
- Soderkopingsan, Southern Sweden
- Model study
- Data on nitrogen concentrations in drainage water from different land uses obtained from monitoring programs in the region – graphs but no raw data provided

This paper presents a dynamic conceptual model for simulation of the hypothetical effect of wetlands on nitrogen export to the coastal zone. An empirically based routine for wetland retention was calibrated separately and incorporated into the model. Scenarios with different location and size of wetlands were analyzed. It was estimated that conversion of 1% of the drainage basin into wetlands would reduce the nitrogen transport by 10-16% and that more than 5% conversion to wetlands is required to reduce transport by 50%. It was concluded that creation of wetlands should be considered primarily downstream from major lakes, in coastal areas, and where summer load is a significant portion of the annual load. The authors concluded that:

- Net reduction of nitrogen transport per unit area of wetland decreases with increasing total area of wetlands in a drainage basin;
- The wetland retention efficiency obtained in studies of individual wetlands can not be extrapolated in a linear fashion to estimate the net reduction of nitrogen transport at the mouth of a whole drainage basin;

- The seasonal hydrological and hydrochemical dynamics are of fundamental importance for wetland retention efficiency, which complicates comparison and extrapolation of results from one region to another.

Bowen, J.L. and I. Valiela. 2002. Nitrogen loads to estuaries: Using loading models to assess the effectiveness of management options to restore estuarine water quality. *Estuaries* 27(3), pp. 482-500.

Abstract:

Nitrogen (N) loading to estuaries has become a major concern for coastal planners. As urban development on coastal watershed continues, estuaries and bays are becoming more eutrophic, and cascading effects are being felt at every trophic level. Managers and stakeholders need to have a suite of effective management tools that can be applied to coastal watersheds to minimize the effects of eutrophication. We applied an N loading model and an estuarine loading model to examine the effectiveness of a suite of potential management options that could be implemented in Waquoit Bay, Cape Cod, Massachusetts. This estuarine system is a case study in which we can explore the relative potential effectiveness of decreasing inputs from wastewater and fertilizer-derived N, diverting nitrogenous runoff from impervious surfaces, altering zoning ordinances, preserving forested tracts of land as well as freshwater and saltwater wetlands, harvesting macroalgae, dredging estuary channels, and exterminating waterfowl. From a combination of simulation results, assessment of the magnitude of loads from different sources, and through different land covers, and the additional consideration of feasibility we identified management options with high, intermediate, and low potential effectiveness. Improvement of septic system performance, use of zoning regulations, preservation of forested tracts and freshwater bodies, and conservation of salt marshes emerged as the most promising avenues to manage N loads in our system. Installation of wastewater treatment plants, controlling fertilizer use, and harvesting macroalgae would potentially have intermediate success. Diversion of runoff from impervious surfaces, dredging, and extermination of waterfowl show little promise at reducing N loads. These conclusions potentially set priorities for decision-makers charged with the management of Waquoit Bay. The same procedures applied to another watershed-estuary system with different land covers and different estuarine features may differ. Evaluation studies like this need to be done for any particular site, since the watershed-estuary coupling and the loads delivered to the receiving estuary could differ. The Waquoit Bay case study provides an example of a protocol that leads to identification of the most promising management options.

Dorge, J. 1994. Modeling nitrogen transformations in freshwater wetlands. Estimating nitrogen retention and removal in natural wetlands in relation to their hydrology and nutrient loadings. *Ecological Modeling* 75/76, pp. 409-420.

- Modelled wetlands
- Denmark
- Model study
- Summary data from several wetlands – no new data

Abstract:

The agricultural utilization of the transition zone between the terrestrial and the aquatic system has strongly reduced these important buffer zones in the last 30 years. The reestablishment of wetlands in relation to the aquatic environment is getting more and more in focus in the debate on eutrophication. A general simulation model has been developed for freshwater wetlands to determine the retention and removal of nitrogen in wetlands as water flows from intensively cultivated farm land through wetlands and into the aquatic system. The model consists of a simple hydrological submodel and a more complex biological submodel including heterotrophic nitrogen dynamics and plant uptake. The whole biogeochemical pathway from mineralization of organic matter to ammonia and further to nitrate in the oxic microzone by nitrifiers, before denitrification, is explicitly modelled. The model has been calibrated with field data from three wetlands with different levels of NO_3^--loading (587–1502 kg NO_3^--N/ha · y) and vegetation. The calculated N-retention varies from 0 to 107 kg N/ha · y and the denitrification from 199 to 743 kg NO_3^--N/ha · y with the lowest value in a *Sphagnum*-dominated wetland and the highest in a reed swamp. The wetland model can be applied to a model system describing the nitrogen turnover and transport from agricultural fertilization through soil and groundwater processes to the final washout into the aquatic environment. Moreover, the model can be used as a prognostic tool for an assessment of the potential effects on the aquatic ecosystem if relevant wetlands were reestablished.

Annotation:

This paper describes a model of nutrient retention and removal in wetlands. The paper discussess important processes (plant uptake, nitrification, denitrification, adsorption, plant decomposition) and their interrelatedness. The model was calibrated with data from three wetland systems in Denmak. Results show the model to be an effective tool for evaluating potential nutrient uptake and removal in wetlands. However, the author notes that the diversity of wetland types precludes capturing the full bandwidth of nutrient removal and retention in them.

Hicks, D.M. and J.A. Moore. 2002. Modeling nitrogen dynamics in treatment wetlands: the use of plant efficiency concepts. *Research & Extension Regional Water Quality Conference 2002.* Online at http://www.swwrc.wsu.edu/conference/Papers/Dana_Hicks.pdf

Abstract:

The ability of macrophytes (plants with tissues that are easily visible) to uptake, store, and then release nitrogen has been utilized in treatment wetlands to remove nitrogen from source waters, but this function of macrophytes is often ignored in models of these systems. One reason is that macrophytes are considered temporary storage units that circulate nitrogen with no net effect. But when the time scale of interest is daily or monthly for water quality discharge permits, we have to be able to estimate the amount and timing of nitrogen uptake and release from the plants in the system. Considering the role of macrophytes will also help make progress toward designing treatment wetlands with more efficient and consistent nitrogen removal. While more and more data are becoming available from treatment wetlands, the primary source of data available on within-stand nutrient cycling is still from studies conducted in natural systems. Since nitrogen levels in treatment wetlands are often many times the levels occurring naturally, it would be convenient to be able to approximate plant biomass and nutrient content with some degree of accuracy when direct sampling is not feasible. Plants in low nitrogen environments have developed nitrogen-conservation mechanisms that allow them to efficiently use and recycle nitrogen. Several studies have investigated the response of plants to increases in nitrogen availability and have shown that plants may become less efficient at nitrogen uptake, use, and resorption before senescence (Shaver and Melillo 1984, Aerts et al. 1992, Aerts and De Caluwe 1994, Aerts et al. 1999, Feller et al. 1999, Richardson et al. 1999). In this paper I describe how plant efficiency concepts are being used to calculate plant nitrogen and biomass values in a nitrogen cycling model that I have created.

Johnes, P.J. 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorous load delivered to surface waters: the export coefficient modeling approach. *Journal of Hydrology* 183, pp. 323-349.

Abstract not available electronically

Johnes, P.J. and D. Butterfield. 2002. Landscape, regional, and global estimates of nitrogen flux from land to sea: errors and uncertainties. *Biogeochemistry* 57/58, pp. 429-476.

Abstract:

Regional to global scale modelling of N flux from land to ocean has progressed to date through the development of simple empirical models representing bulk N flux rates from large watersheds, regions, or continents on the basis of a limited selection of model parameters. Watershed scale N flux modelling has developed a range of physically-based approaches ranging from models where N flux rates are predicted through a physical representation of the processes involved, through to catchment scale models which provide a simplified representation of true systems behaviour. Generally, these watershed scale models describe within their structure the dominant process controls on N flux at the catchment or watershed scale, and take into account variations in the extent to which these processes control N flux rates as a function of landscape sensitivity to N cycling and export. This paper addresses the nature of the errors and uncertainties inherent in existing regional to global scale models, and the nature of error propagation associated with upscaling from small catchment to regional scale through a suite of spatial aggregation and conceptual lumping experiments conducted on a validated watershed scale model, the export coefficient model. Results from the analysis support the findings of other researchers developing macroscale models in allied research fields. Conclusions from the study confirm that reliable and accurate regional scale N flux

modelling needs to take account of the heterogeneity of landscapes and the impact that this has on N cycling processes within homogenous landscape units.

Valiela, I., Bowen, J.L., and K.D. Kroeger. 2002. Assessment of models for estimation of land-derived nitrogen loads to shallow estuaries. *Applied Geochemistry* 17, pp. 935–953.

Abstract:

The performance of several models used to estimate land-derived N loads to shallow receiving estuaries are compared. Models included in the comparison differed in complexity and approach, and predicted either loads or concentrations in estuary water. In all cases, model predictions were compared to measured loads or concentrations, as appropriate. Measured N loads to 9 estuaries on Cape Cod, MA, were obtained as the product of mean concentrations in groundwater about to seep into estuaries multiplied by the annual recharge of groundwater. Measured annual mean N concentrations in estuaries were obtained by extensive sampling surveys. The validity of this procedure to measure loads was verified by comparison against seepage meter data. Responsiveness of model predictions was generally good: predictions increased significantly as measured values increased in 8 of the 10 models evaluated. Precision of predictions was significant for all models. Three models provided highly accurate predictions; correction terms were calculated that could be applied to predictions from the other models to improve accuracy. Four of the models provided reasonable predictive ability. Simulations were run with somewhat different versions of two of the models; in both cases, the modified versions yielded improved predictions. The more complex models tended to be more responsive and precise, but not necessarily more accurate or predictive. Simpler models are attractive because they demand less information for use, but models with more comprehensive formulations, and emphasis on processes tended to perform better. Different models predicted widely different partitioning of land-derived N loads from wastewater, fertilizers, and atmospheric deposition. This is of concern, because mitigation options would be based on such partitioning of predictions. Choice of model to be used in management decisions or for research purposes therefore is not a trivial decision.

10.0 BOGS, FENS, PEATLANDS, MEADOWS

Aerts, R., Verhoeven, J.T.A., and D.F. Whigham. 1999. Plant-mediated controls on nutrient cycling in temperate fens and bogs. *Ecology* 80(7), pp. 2170-2181.

Abstract. This paper reports on patterns in plant-mediated processes that determine the rate of nutrient cycling in temperate fens and bogs. We linked leaf-level nutrient dynamics with leaf-litter decomposition and explored how the observed patterns were reflected in nutrient cycling at the ecosystem level. Comparisons were made among growth forms (evergreen and deciduous shrubs and trees, graminoids and *Sphagnum* mosses) and between mire types (fens and bogs). A literature review showed that the predominant growth form was more important as a determinant of leaf-level nutrient-use efficiency (NUE) than mire type (fen vs. bog). Evergreens had the highest N and P use efficiency. The growth form differences in NUE were mainly determined by differences in N and P concentrations in mature leaves and not by differences in resorption efficiency from senescing leaves. *Sphagnum* leaves had lower N and P concentrations than the other growth forms, but because of a lack of data on nutrient resorption efficiency the NUE of these mosses could not be calculated. Nitrogen use efficiency did not differ among fen and bog species, whereas bog species had a higher P use efficiency than fen species. However, a complete evaluation of mire-type or growth-form effects on NUE is only possible when data become available about nutrient resorption from senescing *Sphagnum* leaves. As leaf-level NUE is negatively correlated with leaf-litter nutrient concentrations, there is a direct link between NUE and litter decomposition rate.

Rates of litter decomposition of *Sphagnum* mosses are lower than in the other growth forms, but there is still much speculation about possible reasons. The role of litter chemistry of *Sphagnum* mosses (including decay inhibitors and decay-resistant compounds) in decomposition especially warrants further study. The strongly deviating nutritional ecology of *Sphagnum* mosses clearly distinguishes fens and bogs from other ecosystems. Moreover, N and P concentrations in mature leaves from vascular plant species from fens and bogs are in almost all cases lower and leaf-level N use efficiency is higher than in species from other ecosystems, irrespective of the growth form considered.

Both literature data and data from a comparative study on soil nutrient cycling in temperate fens and bogs in the United States (Maryland), The Netherlands, and Poland showed that nutrient mineralization did not differ clearly between fens and bogs. The comparative study further showed that cellulose decomposition in bogs was lower than in fens and that nutrient mineralization was higher in forested than in herbaceous mires. The occurrence of dominant growth forms was clearly related to soil nutrient-cycling processes, and observed patterns were in agreement with patterns in the components of NUE as found in the literature study. We conclude that a protocol with standardized procedures for measuring various nutrient-cycling process rates that is used by scientists in various wetland types and geographical regions is a useful tool for unravelling large-scale patterns in soil nutrient-cycling processes in wetlands and for linking plant-mediated nutrient dynamics with ecosystem nutrient-cycling processes.

Bridgham, S.D., Updegraff, K., and J. Pastor. 1998. Carbon, nitrogen, and phosphorus mineralization in northern wetlands. *Ecology* 79(5), pp. 1545-1561.

Abstract. We examined rates of C, N, and P mineralization in soils from 16 northern Minnesota wetlands that occur across an ombrotrophic–minerotrophic gradient. Soils were incubated at 30°C under aerobic and anaerobic conditions for 59 wk, and the results were fit with a two-pool kinetic model. Additionally, 39 different soil quality variables were used in a principal components analysis (PCA) to predict mineralization rates.

Mineralization of C, N, and P differed significantly among wetland types, aeration status (aerobic vs. anaerobic), and their interaction term. Despite low total soil N and P, there was a rapid turnover of the nutrient pools in ombrotrophic sites, particularly under aerobic conditions. On a volumetric basis, C and N mineralization increased in a predictable manner across the ombrotrophic–minerotrophic gradient, largely due to increasing soil bulk density. However, P mineralization per cubic centimeter remained relatively high in the bogs. The higher total P content of more minerotrophic soils appears to be offset by greater P immobilization due to geochemical sorption, yielding overall lower availability.

Total C turnover rates were relatively similar among sites, despite large differences in soil quality. We suggest that, over time, the decay rates of organic matter in different wetland communities converge to a common rate. In contrast, CH_4 production was extremely low in ombrotrophic peats.

The apparent labile pools of N (N_0), P (P_0), and C (C_0) were generally <10% of their respective total pool sizes, except for P_0 in the bogs, which constituted up to 33% of total soil P. From 10% to 87% of the N, P, and C mineralized after 59 wk was derived from their respective labile pools.

A simple group of variables describing the physical degree of decomposition of organic matter was often as good as, or superior to, more complicated chemical analyses in predicting C, N, and P mineralization. Because peats are classified and mapped according to these variables, it should make scaling efforts in landscape analyses much more tractable.

Large differences in mineralization rates in northern wetland communities demonstrate that climate change models should not consider these areas as homogeneous entities. Our C mineralization results suggest that soil respiratory response to climate change (as CO_2 and CH_4) will vary considerably in different wetland communities. Our results also suggest that the common perception that more ombrotrophic sites are inherently more nutrient deficient needs to be reassessed.

Busse, L.R. and G. Gunkel. 2001. Riparian alder fens - source or sink for nutrients and dissolved organic carbon? - 1. Effects of water level fluctuations. *Limnologica* 31, pp. 307-315.

Abstract:

The biogeochemistry of riparian alder wetlands was studied from 1995 to 1997. Nutrient and DOC chemistry was related to water level changes. The spatial and temporal patterns of nutrients (P and N) and dissolved organic carbon (DOC) were measured in the surface water flowing through a riparian alder fen and in the adjacent creek. Nutrient and DOC concentrations were extremely variable temporally but not spatially within the wetland. In the wetland and the adjacent creek concentrations of NO3-N, PQ-P and DOC were homogenous during high-flow periods and frozen conditions. After low-flow conditions water bodies were isolated from the creek. The concentration of NH4-N, PO4-P and DOC in these isolated water bodies was significantly higher than in the adjacent creeks due to low oxygen levels. Enclosures of different sizes were installed in the wetland to study possible release rates. A large enclosure experiment in the flooded alder fen showed the same concentrations as after high-flood conditions except for DOC. The DOC concentrations were enriched in the large enclosure after decomposition from leaf litter during fail season. Small enclosures with low oxygen levels confirmed data obtained from low-flow conditions. The release rates were calculated for low flow conditions from small enclosure experiments for 2 months a year when the alder fen is not flooded. The rates for July and August were 11.6 kg/ha NH4-N, 8.6 kg/ha PO4-P and 57.6 kg/ha DOC. The DOC concentrations for fall estimated from the large enclosure-experiments were 168.2 kg/ha for the months September and October. This means possible output rates of N, P and DOC during the summer and DOC during fall in the adjacent river system. This can cause eutrophication and organic pollution depending on the length of the low-flow conditions and the size of the alder fen. Water level changes must be regarded as important for the management of riparian wetlands such as alder fens. The riparian alder system may vary from a nutrient sink to a nutrient source at different times of a year depending on high or low water levels.

Busse, L.R. and G. Gunkel. 2002. Riparian alder fens - source or sink for nutrients and dissolved organic carbon? - 2. Major sources and sinks. *Limnologica* 32, pp. 44-53.

Abstract:

Natural riparian forest wetlands are known to be effective in their ability to remove nitrate by denitrification and sediments with attached phosphorus via sedimentation. On the other hand, litter input and decomposition is a process of crucial importance in cycling of nitrogen and phosphorus in a forest ecosystem.

In this study we investigated the amount of nitrogen and phosphorus entering the alder fen ecosystem through leaf litter and its decomposition and the removal capacity of nitrogen and phosphorus by measuring denitrification and sedimentation in the alder fen.

We found an average input of leaf litter during fall 1998 of 226 g m -2 yr -1 DW with nutrient concentration of 0.17% P and 1.6% N. This means a yearly input of 0.4 g m -2 yr -1 P and 3.6 g m -2 y -1 N. The decomposition of leaf litter using litter bags with small and large mesh size resulted in bags with macroinvertebrates (large mesh size) and without macroinvertebrates (small mesh size). After 57 days the litter bags with macroinvertebrates had a decomposition rate of 79%.

Denitrification was measured in May and June of 1997 using the acetylene inhibition technique on intact soil cores and slurry-experiments. The average annual denitrification rate was 0.2 g m -2 yr -1 N using data from the core experiments. The denitrification rate was higher after addition of nitrate, indicating that denitrification in the riparian alder fen is mainly controlled by nitrate supply.

The sedimentation rate in the investigated alder fen ranged from 0.47 kg m -2 yr -1 DW to 4.46 kg m -2 yr -1 DW in 1998 depending on the study site and method we used. Sedimentation rates were lower in newly designed plate traps than in cylinder traps. The alder fen also showed lower rates than the adjacent creek Briese. Average phosphorus removal rate was 0.33 g m -2 yr -l P.

Input sources for the surface water of the alder fen are sediment mineralization and decomposition of leaf litter; output sources are sedimentation and denitrification. This study showed that a nutrient input of 24.58 kg ha -1 yr -1 N, 8.8 kg ha -1 yr -1 P and 419 kg ha -1 yr -1 DOC into the surface water of the alder fen is possible. Alder fens cannot improve water quality of an adjacent river system. This is only true for a nearly pristine alder fen with the hydrology of 10 months flooded conditions and 2 months non-flooding conditions a year.

Chapin, C.T., Bridgham, S.D., and J. Pastor. 2004. pH and nutrient effects on above-ground net primary production in a Minnesota, USA bog and fen. *Wetlands* 24(1), pp. 186-201.

Abstract:

Nutrient limitation is often assumed to be similar among the species of a plant community. However, limitation can differ among ecosystems and among life forms and individual species within a particular ecosystem. Peatlands have some of the lowest nutrient availabilities and highest acidities among wetland types, but the relative roles of nutrient limitation and pH stress in structuring peatland plant communities are unknown. Accordingly, we measured changes in above-ground net primary production (ANPP) and percent cover of plants to additions of low levels of N, P, and calcium carbonate in a bog and fen in northern Minnesota, USA. Plots were treated for three years with a combination of 2 or 6 g N m22 yr21 as ammonium, 0.67 or 2 g P m22 yr21, and/or calcium carbonate to raise the pH of the bog from 3.8 to 4.9 and the pH of the fen from 4.9 to 6.4. In the bog, the low N treatment increased ANPP, whereas the high N treatment inhibited ANPP. Lime addition also stimulated ANPP. The whole-community bog response was largely due to bryophytes, which accounted for 76% of ANPP on average. However, the productivity of the shrub community (18% of total ANPP) increased with P additions but only during the third year of fertilizer application. Productivity of the bog graminoids did not respond significantly to any addition. Fen ANPP was stimulated by P addition, but the effect was isolated to graminoids (95% of total ANPP), and this was largely due to the response of *Carex exilis*. Our results suggest that low nutrient availability does not necessarily simply nutrient limitation of peatland plant communities. Furthermore, life forms and individual species responded differently, indicating that there are several levels of nutrient limitation within each peatland community. In particular, bog *Sphagnum* mosses appear to have a very low tolerance for N. Production and community structure were controlled by N-availability and pH in the bog and by P-availability in the fen.

Hemond, H.F. 1980. Biogeochemistry of Thoreau's Bog, Concord, Massachusetts. *Ecological Monographs* 50(4), pp. 507-526.

Abstract. Thoreau's Bog in Concord, Massachusetts, is a floating-mat *Sphagnum* bog developed in a glacial kettle hole. Low shrub vegetation of the open mat is dominated by *Chamaedaphne calyculata*; trees include scattered *Picea mariana* and *Larix laricina*. Hydrological investigations show the bog to be ombrotrophic, with an annual water input of 1.45 m and an annual runoff of 0.24 m. Corresponding metal inputs are 88, 132, and 54 $mg \cdot m^{-2} \cdot yr^{-1}$ for K, Mg, and Pb, respectively. K and Mg are vertically distributed in the bog profile in accord with the inhomogeneous ion exchange chemistry of peat, while lead is distributed in accord with historical trends in atmospheric lead fallout. Isotopic dating using ^{210}Pb is a valuable tool for determining net peat accumulation rate, which is 180 $g \cdot m^{-2} \cdot yr^{-1}$. Annual storage rates of K, Mg, and Pb in peat amount to 36, 54, and 46 $mg \cdot m^{-2} \cdot yr^{-1}$, respectively. Bog acidity (pH = 3.8) is maintained by organic acids at concentrations of 10^{-3} eq/L. The effect of cation exchange on bog acidity is modest, while the much larger contribution of "acid rain" is offset by alkalinity increases of the same magnitude resulting from sulfate reduction and nitrate uptake. These latter processes are, in effect, a strong buffer mechanism against acid rain. ^{210}Pb dating and historical records suggest that the floating mat is relatively young, perhaps as few as 500 yr old. These data raise the possibility that the bog is not a relict of colder, early postglacial periods, but instead, may have developed under modern climatic conditions.

Howes, B.L. and J.M. Teal. 1995. Nutrient balance of a Massachusetts Cranberry Bog and Relationships to Coastal Eutrophication. *Environmental Science and Technology* 29(4):960-974.

Nutrient fluxes in surface waters and processes controlling nutrient retention and loss were measured through 1 yr in a 15-ha cranberry bog discharging to a shallow embayment of Buzzards Bay, MA. Continuous measurements of streamflow and nutrient concentrations, periodic measures of nutrient release by sediments, inputs from rainfall, and exchanges with plant pools were used to construct a nitrogen balance for the bog and to estimate dissolved phosphate fluxes. Nutrient losses were small during the growing season and greatest in the fall with plant senescence and harvest. Of nitrogen inputs to the bog, 33% was fertilizers, 8% was rain, and 59% was in inflowing streamwaters. While the bog plants and sediments were net sinks for nitrogen, the fertilizers associated with cranberry agriculture resulted in the bog serving as a source of nitrogen to outflowing streamwaters discharging to the adjacent bay. Net losses of 25 kmol of N were almost completely to the outflowing stream (93%) with harvested berries and leaves accounting for 5% and 2%, respectively. NH4+ accounted for most of the N loss to streamflow, 53%. Annual $P0_4^{3-}$ losses of 4.8 kmol were associated mainly with reduced soil oxidation due to flooding for harvest and frost protection. Net losses of total N, 1.7 kmol ha^{-1} yr^{-1}, or DIN + PON, 1.8 kmol ha^{-1} yr^{-1}, were similar to a surface water-dominated freshwater wetland but much lower than the nitrogen contribution from an adjacent residential development.

Leonardson, L. Bengtsson, L., Davidsson, T., Persson, T.and U. Emanuelsson. 1994. Nitrogen retention in artificially flooded meadows Nitrogen retention in artificially flooded meadows. *Ambio* 23(6), pp. 332-341.

Abstract not available electronically

Annotation:

- Constructed wetland
- Southern Sweden
- Field study
- Reports data total N, NO3-N, NH4-N, organic N in inflow and outflow water; also plant uptake (biomass) and denitrification

This study looked at nitrogen whether artificial flooding of meadows would be a possible means of reducing the nitrogen content in streams and rivers. Two case studies were done in sandy and peaty soil. Overall nitrogen retention was estimated by mass balance. Denitrification activity and plant biomass incorporation of nitrogen were measured, and used to complement the mass-balance data. Results showed that total nitrogen retention achieved during artificial flooding amounted to 0.3 to 0.7 mol N m^{-2} yr^{-1} (about 15% of the total N load) in two of the meadows, and zero in a third. In the sandy/organic soil, denitrification was enhanced by the artificial flooding, while in the peat area the activity was lower than in a nonflooded reference area. Longer irrigation periods resulted in higher total nitrogen retention. Under identical irrigation regimes, peat soil was more favorable for nitrogen retention than sandy/organic soil. Spatial heterogeneity was evaluated, and results showed the maximum distance of spatial dependence for denitrification was 49-87 cm. Artificial flooding stimulated nitrogen uptake by plants. Peat soil was most favorable for plant growth and nitrogen incorporation.

Schwintzer, C.R. 1979. Nitrogen fixation by Myrica gale root nodules Massachusetts wetland. *Oecologia* 43, pp. 283-294.

Abstract not available in electronically.

Verhoeven, J.T.A. 1986. Nutrient dynamics in minerotrophic peat mires. *Aquatic Botany* 25, pp. 117-137.

- Peat mires/fens/bogs

- Various locations in the United States and Europe
- Literature Review

Abstract:

This paper is a literature review on the dynamics of nitrogen, phosphorus and potassium in minerotrophic mires. Minerotrophic mires are wetlands with a peat soil of more than 40 cm thick, which receive water and nutrients not only from precipitation, but also from inflowing streams and ground-water. Typical examples of such mires are fens, *Papyrus* swamps and *Ciadium* mires.

In a hydrological gradient from peat bogs with no lateral water movement to lentic riverine wetlands with strong currents, minerotrophic mires are intermediate. They are of two main types: quaking mires with a floating mat of vegetation on top of a water layer, and mires with a continuous peat layer down to the bottom sediment or bedrock.

The mire water is a mixture of rain-water and ground-water. Calcium is the most predominant cation, bicarbonate or sulphate are the predominant anions. Minerotrophic mires can be distinguished from ombrotrophic ones (receiving only rain-water) by their higher pH (>4) and calcium concentration (> 1 ppm). The concentrations of inorganic N and P in the mire water are generally low. Ammonium is the main inorganic N component. The concentrations of N, P and K measured by different authors in a wide variety of mires fall within remarkably narrow ranges.

The peat soil of the mires contains large amounts of N, P and K. Most of the N and P is sequestered in organic material. The N content of peat is remarkably similar in widely different mires. The P and K contents show much more variation. "Available" N and P amount to only 0.6–1.2% and 0.2–3% of the total, respectively.

The availability of N and P to the vegetation is determined by the mineralization of organic matter and by the supplies by rain- and ground-water. The mineralization of organic matter is the result of bacterial break-down. The processes of decomposition and mineralization in mires are discussed in some depth.

The fixation of N_2 by bacteria is a significant N input to minerotrophic mires. The circumstances for denitriflcation are very suitable, but the actual rates are probably low due to the scarcity of NO_3^-.

The role of the vegetation in the nutrient dynamics o f mires is discussed. In mires with a high plant biomass, generally high amounts of N, P and K are contained in the plant material. An interesting exception form the *Cladium* mires in Florida, that have a high biomass, but low P and N contents. In many minerotrophic mires plant growth is limited by the availability of N or P. The importance of seasonal translocation of nutrients in these mires remains questionable.

A qualitative picture is given of the inputs and outputs of N, P and K in minerotrophic mires. The nutrient stocks in three compartments, viz. water, peat soil and vegetation are given for three mire systems in different parts of the world. The similarities between these are striking.

An interesting point for further research is the balance between inputs, outputs and sequestering of nutrients in these systems, that are often considered as accumulating C, N and P.

Annotation:

Minerotrophic peat mires are bogs which are rich in mineral ions, receive ground and surface water, and support wetland vegetation. These wetlands are common in glaciated regions such as northeastern United States, although not many have been studied. The role of nutrient cycling within bogs has not been extensively investigated, but this literature review by Verhoeven attempts to summarize the general characteristics of nutrient cycling (and geochemistry) within these wetland ecosystems. The review contains tables listing the chemical characteristics of water, soils, and plant biomass in mires. In terms of the nutrient dynamics and distribution within mires/bogs, Table V lists the percentage of nitrogen, phosphorous, and potassium in the 3 compartments of the ecosystem. Although, the geographic locations of the three bogs are different, the distribution on the nutrients within these three compartments is similar. The peat and litter compartment contains the majority of the three nutrients (over 97% of nitrogen, most of which is organic). Surprisingly little nitrate is leached out and transformed from the multitude of organic nitrogen in mires/bogs. Nitrogen fixation has been observed in these ecosystems, but little quantitative information is known. Denitrification is thought to be potentially significant, but is limited by the availability of nitrate. Studies have supported this observation; however Verhoeven notes that measurements of denitrification rates in natural minerotrophic mires/bogs are lacking. Despite these data, Verhoeven states that a quantitative understanding of nutrient transport and cycling in mires/bogs is still needed. This review offers the reader a good starting reference point when researching bogs/fens, yet as Verhoeven indicates, more recent information and data are needed to obtain a quantitative understanding of the biogeochemical cycling of nitrogen.

Wiegner, T.N., and S.P. Seitzinger. 2004. Seasonal bioavailability of dissolved organic carbon and nitrogen from pristine and polluted freshwater wetlands. *Limnology and Oceanography* 49(5), pp. 1703-1712.

Abstract:

We examined the chemical composition and bioavailability of dissolved organic carbon (DOC) and nitrogen (DON) from two pristine and two polluted cedar bog wetlands across three seasons. Pristine and polluted wetlands differed in DOC and DON concentrations, chemical characteristics, and bioavailability. DOC and DON concentrations were higher in the polluted than in the pristine wetlands. In contrast, a higher percentage of the dissolved organic matter (DOM) was more aromatic in the pristine (54% ± 19) than in the polluted (27% ± 4) wetlands. A higher percentage of DOC was bioavailable in the pristine (22% ± 9) than the polluted (12% ± 4) wetlands. A similar percentage of DON was consumed in both the pristine (33% ± 25) and polluted (28% ± 25) wetlands. Seasonally, the bioavailability of DOC and DON varied and differed between the pristine and polluted wetlands. The availability of phosphate appeared to affect the amount of DOC incorporated into bacterial biomass, whereas inorganic nutrient availability did not affect the assimilation of DON. Bioavailable DOC primarily fueled bacterial respiration, whereas DON supported bacterial growth. Overall, our results demonstrate that anthropogenic activities and season affect the quantity and quality of wetland DOM exported to rivers and that different factors control the utilization and fate of DOC and DON within the bacterial community.

11.0 REVIEWS

Bowden, W.B. 1987. The biogeochemistry of nitrogen in freshwater wetlands. *Biogeochemistry* 4, pp. 313-348.

Abstract. The biogeochemistry of N in freshwater wetlands is complicated by vegetation characteristics that range from annual herbs to perennial woodlands; by hydrologic characteristics that range from closed, precipitation-driven to tidal, riverine wetlands; and by the diversity of the nitrogen cycle itself. It is clear that sediments are the single largest pool of nitrogen in wetland ecosystems (100's to 1000's g N m^{-2}) followed in rough order-of-magnitude decreases by plants and available inorganic nitrogen. Precipitation inputs (< 1–2 g N m^{-2} yr^{-1}) are well known but other atmospheric inputs, e.g. dry deposition, are essentially unknown and could be as large or larger than wet deposition. Nitrogen fixation (acetylene reduction) is an important supplementary input in some wetlands (< < 1–3 g N m^{-2} yr^{-1}) but is probably limited by the excess of fixed nitrogen usually present in wetland sediments.

Plant uptake normally ranges from a few g N m^{-2} yr^{-1} to ~ 35 g N m^{-2} yr^{-1} with extreme values of up to ~ 100 g N m^{-2} yr^{-1}. Results of translocation experiments done to date may be misleading and may call for a reassessment of the magnitude of both plant uptake and leaching rates. Interactions between plant litter and decomposer microorganisms tend, over the short-term, to conserve nitrogen within the system in immobile forms. Later, decomposers release this nitrogen in forms and at rates that plants can efficiently reassimilate.

The NO_3 formed by nitrification (< 0.1 to 10 g N m^{-2} yr^{-1}) has several fates which may tend to either conserve nitrogen (uptake and dissimilatory reduction to ammonium) or lead to its loss (denitrification). Both nitrification and denitrification operate at rates far below their potential and under proper conditions (e.g. draining or fluctuating water levels) may accelerate. However, virtually all estimates of denitrification rates in freshwater wetlands are based on measurements of potential denitrification, not actual denitrification and, as a consequence, the importance of denitrification in these ecosystems may have been greatly over estimated.

In general, larger amounts of nitrogen cycle within freshwater wetlands than flow in or out. Except for closed, ombrotrophic systems this might seem an unusual characteristic for ecosystems that are dominated by the flux of water, however, two factors limit the opportunity for N loss. At any given time the fraction of nitrogen in wetlands that could be lost by hydrologic export is probably a small fraction of the potentially mineralizable nitrogen and is certainly a negligible fraction of the total nitrogen in the system. Second, in some cases freshwater wetlands may be hydrologically isolated so that the bulk of upland water flow may pass under (in the case of floating mats) or by (in the case of riparian systems) the biotically active components of the wetland. This may explain the rather limited range of N loading rates real wetlands can accept in comparison to, for example, percolation columns or engineered marshes.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., and B.J. Cosby. 2003. The Nitrogen Cascade. *BioScience* 53(4), pp. 341.

Abstract:

Human production of food and energy is the dominant continental process that breaks the triple bond in molecular nitrogen (N2) and creates reactive nitrogen (Nr) species. Circulation of anthropogenic Nr in Earth's atmosphere, hydrosphere, and biosphere has a wide variety of consequences, which are magnified with time as Nr moves along its biogeochemical pathway. The same atom of Nr can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health. We call this sequence of effects the nitrogen cascade. As the cascade progresses, the origin of Nr becomes unimportant. Reactive nitrogen does not cascade at the same rate through all environmental systems; some systems have the ability to accumulate Nr, which leads to lag times in the continuation of the cascade. These lags slow the cascade and result in Nr accumulation in certain reservoirs, which in turn can enhance the effects of Nr on that environment. The only way to eliminate Nr accumulation and stop the cascade is to convert Nr back to nonreactive N_2.

Howard-Williams, C. 1985. Cycling and retention of nitrogen and phosporus in wetlands: a theoretical and applied perspective. *Freshwater Biology* 15, pp. 391-431.

Abstract not available electronically.

Jansson M, Andersson, R., Berggren, H. and L. Leonardson . 1994. Wetlands and lakes as nitrogen traps. *Ambio* 23(6), pp. 320-325.

Abstract not available electronically.

Annotation:

- Stream
- River Raan, Southern Sweden
- Field study
- Reported total N, nitrogen retention, denitrification rate, water discharge, and water temperature

This study developed mass balance calculations for a small stream and a small pond. In addition, denitrification activity and limiting factors for the denitrification were analyzed in the laboratory using the acetylene block technique. Total annual nitrogen retention was less than 3% of the total nitrogen transport in the stream. Retention in the pond was greater than in the rest of the river. Significant nitrogen retention (20-50%) occurred only during low flow periods in the summer. Under these circumstances denitrification losses correspond to more than half of the total nitrogen retention. On an annual basis denitrification was responsible for 30-40% of total retention. The discharge rate was by far the most critical factor in determining nitrogen retention both in running water and the pond.

Johnston, C.A. 1991. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. *Critical Reviews in Environmental Control* 21(5,6), pp. 491-565.

- Freshwater wetlands
- No specific geographical location – deals with all freshwater wetlands
- Review article
- Reports summary data on nitrogen content in various types of wetland soil, plants, nitrogen accumulation rates for certain wetlands, and denitrification rates from several lab studies

Abstract not available electronically.

Annotation:

This article reviews the mechanisms of nutrient retention in freshwater wetlands, and discusses effects on surface water quality. Sedimentation, plant uptake, litter decomposition, retention in soil, and microbial processes are discussed as they relate to nutrient retention at various time scales. Plant uptake and litter decomposition provide short- to long-term retention of nutrients, depending on rates of leaching, translocation to and from storage structures, and the longevity of plant tissues. Plant litter can also provide a substrate for microbial processing of nutrients, particularly via denitrification. Wetland soils sorb nutrients and provide the environment for aerobic and anaerobic microorganisms that perform nitrification-denitrification, the latter of which permanently removes nitrogen from the system.

Johnston, C.A. 1993. Mechanisms of wetland water quality interaction. Ch. 30 in Constructed Wetlands for Water Quality Improvement. GA Moshiri, Ed. Lewis Publishers Boca Raton.

Abstract not available electronically.

Johnston, C., Johnson, T., Kuehl, M., Taylor, D. and J. Westman. 1990. The effects of freshwater wetlands on water quality: a compilation of literature values. Report prepared for the Enviornmental Protection Agency Novermber 15, 1990

- Freshwater wetlands
- Throughout the US
- Review article
- Reports summary data on nitrogen content in various types of wetland soil, plants, nitrogen accumulation rates for certain wetlands, and denitrification rates from several lab studies

Abstract not available electronically

Annotation:

This report provides a summary of data from the literature about various mechanisms by which freshwater wetlands retain nutrients and contaminants. Biogeochemical processes that control nitrogen cycling are discussed. Summary data from a variety of studies on nutrient retention and transformation (e.g. atmospheric deposition, denitrification, standing stocks in vegetation, etc.) are given. Soils constitute the major storage compartment for nutrients, with long-term vegetation storage (trees, woody tissues, and rhizomes) also important. Most studies measured standing stock for green tissues and litter, which provide only short-term storage. The authors note that, due to differences in storage times for different wetland components, standing stock measures don't necessarily reflect the annual effect of these mechanisms (i.e. soil retention, plant uptake) on water quality. Nitrogen removal effeciencies (difference between outflow and inflow) ranged from -35% to 95% in a set of wetlands for which data was available.

Reddy, K.R. and W.H. Patrick. 1984. Nitrogen transformations and loss in flooded soils and sediments. *Critical Reviews in Environmental Control* 13(4), 273-302.

Abstract not available electronically.

Stoddard, J.L. 1994. Long-term changes in watershed retention of nitrogen. Ch. 8 in Environmental Chemistry of Lakes and Reservoirs. LA Baker, Ed. Advances in Chemistry Series #237. American Chemical Society, Washington, DC.

- Terrestrial watersheds and wetlands in general
- No specific location
- Review article
- Provides summary data on nitrogen deposition on various watersheds, as well as summary data on pH, NO3- in several lakes and streams throughout the United States

Abstract not available electronically.

Annotation:

This article discusses nitrogen retention in watersheds undergoing increased nitrogen deposition from atmospheric sources. When the supply of nitrogen exceeds demand by plants and soil microbes, nitrogen saturation occurs. This can lead to increased leaching of nitrogen to surface waters. Nitrogen cycling, nitrogen assimilation, and nitrogen leaching are discussed on a watershed scale. A sequence of recognizable stages in nitrogen saturation, originally defined by Aber et al (1989, article described above) is recognized. These stages are as follows:

- Stage 0: inputs of N from atmospheric sources are at background levels and watershed losses of N are negligible.
- Stage 1: increased deposition of N; effects on terrestrial ecosystem not evident. A fertilization effect results in increased ecosystem production and tree vigor. Retention of N is very efficient and little or no N is lost annually to surface waters that drain the watershed.
- Stage 2: Subtle, nonvisual effects occur. Fine root mass decreases, foliar biomass decreases, and net primary production decreases relative to stage 1. Nitrate assimilation may increase at this stage. The phase between Stage 1 and 2 is called nitrogen saturation.
- Stage 3: Net primary production, foliar biomass, and nitrate assimilation decrease at this phase, while foliar N concentration increases; ecosystem decline is evident. Nitrate leaching and N_2O emission increase. The most advanced stages of N saturation usually occur in regions with the most elevated rates of N deposition.

Evidence from various areas is presented and atmospheric N deposition is said to be contributing to degredation of water quality in several regions of the United States.

Straughan Environmental Services, Inc. 2003. Nitrogen Sequestration in Headwater Streams. Prepared for: Christine Conn Maryland Department of Natural Resources Power Plant Research Program Tawes State Office Building Annapolis, Maryland 21401.

- Streams
- Based on data from various streams and rivers
- Literature review
- No raw data presented

Abstract:

The Maryland Power Plant Research Program (PPRP), which is housed within the Maryland Department of Natural Resources (MDNR), is responsible for conducting a consolidated review of all issues related to power generation including environmental considerations. Fossil fuel power generation results in air emissions of several Environmental Protection Agency criteria pollutants, including NO_x. Atmospheric deposition of nitrogen to land and water surfaces introduces a significant amount of nitrogen to the Chesapeake Bay and contributes to an excess of nitrogen in both terrestrial and aquatic ecosystems. PPRP is studying the potential for enhancing the biological removal of nitrogen in headwater streams as a nitrogen pollution control strategy, relevant to power plant licensing conditions. Straughan Environmental Services, Inc. (SES), under the direction of Versar, Inc., conducted a literature search to identify the range of issues and information available to support the PPRP in evaluating the ability of headwater streams to process nitrogen. Preliminary research indicates these streams perform a significant amount of nitrogen sequestration and that this process could be enhanced by improving water quality in biota poor or acidified streams, and by implementing certain stream restoration design characteristics. This literature review supports the PPRP goal of protecting Maryland's natural resources while maintaining our power-generation infrastructure.

Annotation:

This report provides a review of literature on nitrogen attenuation in streams and rivers. Findings indicate that streams do retain nitrogen. Headwater streams and the hyporheic zone are areas of active nitrogen processing. Flow rates, stream hydrology, sediment characteristics, and the biota affect nitrogen uptake. The dominant process for nitrogen retention is denitrification.

vanBreeman, N., Boyer, E.W., Goodale, C.L., Jaworski, N.A., Paustian, K., Seitzinger, S.P., Lajtha, K., Mayer, B., VanDam, D., Howarth, R., Nadelhoffer, K.J., Eve, M., and G. Billen. 2002. Where did all the nitrogen go? Fate of nitrogen inputs to large watersheds of the northeastern USA. *Biogeochemistry* 57/58, pp. 267-293.

- Mixed use watersheds
- Northeastern US
- Review article based on data from 16 watersheds
- Reports total nitrogen inputs, storage, losses

Abstract. To assess the fate of the large amounts of nitrogen (N) brought into the environment by human activities, we constructed N budgets for sixteen large watersheds (475 to 70,189 km^2) in the northeastern U.S.A. These watersheds are mainly forested (48–87%), but vary widely with respect to land use and population density. We combined published data and empirical and process models to set up a complete N budget for these sixteen watersheds. Atmospheric deposition, fertilizer application, net feed and food inputs, biological fixation, river discharge, wood accumulation and export, changes in soil N, and denitrification losses in the landscape and in rivers were considered for the period 1988 to 1992. For the whole area, on average 3420 kg of N is imported annually per km^2 of land. Atmospheric N deposition, N_2 fixation by plants, and N imported in commercial products (fertilizers, food and feed) contributed to the input in roughly equal contributions. We quantified the fate of these inputs by independent estimates of storage and loss terms, except for denitrification from land, which was estimated from the difference between all inputs and all other storage and loss terms. Of the total storage and losses in the watersheds, about half of the N is lost in gaseous form (51%, largely by denitrification). Additional N is lost in riverine export (20%), in food exports (6%), and in wood exports (5%). Change in storage of N in the watersheds in soil organic matter (9%) and wood (9%) accounts for the remainder of the sinks. The presence of appreciable changes in total N storage on land, which we probably under-rather than overestimated, shows that the N budget is not in steady state, so that drainage and denitrification exports of N may well increase further in the future.

Annotation:

This paper evaluates nitrogen inputs, retention and losses in 16 watersheds. This analysis shows denitrification rates in rivers to be lower than that seen in Seitzinger et al. (2002). Forest accretion following logging was seen as a long-term nitrogen retention mechanism. Urban forest soils were found to store more nitrogen than rural forests of the same species and soil type, due to buildup of soil organic matter and high nitrogen inputs.

12.0 FRESHWATER EMERGENT

Bartlett, M.S., Brown, L.C., Hanes, N.B., and N.H. Nickerson. 1979. Denitrification in freshwater wetland soil. *Journal of Environmental Quality* 8(4), 460-464.

Abstract not available in electronic format

Bernard, J.M. and G. Hankinson. 1979. Seasonal changes in standing crop, primary production, and nutrient levels in a Carex rostrata wetland. *Oikos* 32, pp. 328-336.

Abstract not available in electronic format.