Literature Review:

Nitrogen Sequestration in Headwater Streams

December 2003

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Introduction

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 NOx. 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.

Literature Search Methodology

In conducting the research, SES used a variety of sources including the Internet, numerous general references, and scientific publications found at the United States National Agricultural Library and the Hood College Library. SES identified over 40 literature sources pertaining to streams and the processing and removal of nitrogen from surface water. Several ongoing studies are being conducted throughout the United States by scientists associated with the Lotic Intersite Nitrogen Experiment (LINX). Most of the studies conducted by these scientists are taking place in the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, the southern Appalachian mountains of eastern Tennessee, and other national forests throughout the U.S. SES specifically targeted the literature focused on headwater streams during the literature search, but included more general resources where appropriate. These resources were obtained from various scientific journals so the chance for bias in these articles is minimal.

Literature Search Findings

The following table provides a compilation of summaries and data collected from the literature search. SES conducted the literature search by looking for answers to the following questions:

1. How is nitrogen cycled through the environment?
2. How have humans altered the availability of nitrogen in the environment?

3. How is nitrogen released to streams?
4. How is nitrogen processed in streams?
5. What physical and chemical characteristics increase or limit the efficiency of nitrogen removal in streams?
6. What biological processes increase or limit the efficiency of nitrogen removal in streams?
7. What is the efficiency of nitrogen removal within streams?
8. How can existing streams be enhanced to promote greater nitrogen sequestration? and
9. How can design goals be implemented? Summary of further research questions.

The narrative that follows Table 1 consolidates the research results by topic, with a summary preceding each topic list. The narrative is followed by reprints of each article or reference included in this review.

Table 1

1 How is nitrogen cycled through the environment?

Air emissions from fossil fuel power generation introduce nitrogen (N) into the environment. The range of literature regarding N cycling indicates that certain elements of the nitrogen cycle are considered to be established facts, such as:

- N, as N_2 gas, makes up approximately 78% of the earth's atmosphere;
- N is a necessary component of plant growth and becomes available to plants once it has been "fixed" or converted to nitrate (NO_3) or ammonium (NH_4);
- N is "fixed" through the process of nitrification by N-fixing organisms such as microbes, bacteria, or legumes, or by lightning;
- Plants uptake N in the form of NO_3 or NH_4 and it is stored until it is released into the soil through decomposition; and
- Denitrification by bacteria and microbes in soils or stream sediments converts NO_3 back to N_2, and releases it harmlessly into the atmosphere (see Figure 1).

Studies have shown that nutrient levels in streams are lower than nutrient levels in groundwater inputs, indicating that streams are important nutrient sinks.

Author	**Summary of Findings**
Bernhardt, E.S.	Stream nutrient levels are lower than nutrient levels in groundwater inputs, indicating the potential importance of stream processes in reducing nutrient concentrations.
Bernhardt, E.S., R.O. Hall, Jr., and G.E. Likens.	Nitrification is essential in upland soils to decrease the concentration of NO_3 found downstream. Nitrifiers oxidize NH_4 to NO_3 and use that energy to fix carbon dioxide (CO_2).
Ecological Society of America.	Although N_2 makes up 78% of the atmosphere, it is a limiting factor controlling the functions of ecosystems. This is because it only becomes available to organisms after it has been "fixed" or altered to NO_3 or NH_4 by N fixing organisms such as soil microbes and legumes, or by lightning.
Gardner, R.H., et al.	N is deposited from the atmosphere and is absorbed into the soils, or taken up by plants. The process of converting N_2 gas into NH_4, or N fixation, is only a small, additional source of N.
Hamilton, S.K., et al.	"Accelerated rates of nitrification and denitrification enhance the emission of nitrous oxide, a potent greenhouse gas, to the atmosphere."
Kimball, J.W.	79% of the atmosphere is comprised of N_2 gas. However, plants need a fixed form of N, as NO_3, NH_3, or urea, $(NH_2)2CO$. This process occurs through N fixation, decay and nitrification. Denitrification returns N to the atmosphere. Microorganisms are needed for all four of these processes.

Author	Summary of Findings
Martin, L.A., et al.	Denitrification occurs when bacteria oxidize organic carbon while using NO_3 as an electron acceptor. This produces N_2O and N_2 and removes available N from a system.
Melillo, J.	80% of the Earth's atmosphere is comprised of molecular N. N is naturally fixed in the environment by chemical processes such as lightning, and biological processes involving N-fixing bacteria.
Pidwirny, M.J.	Plants need NH_4 and NO_3; therefore, N is a limiting nutrient necessary for plant growth. N is stored primarily in living or dead organic matter.
Simonin, H.A., and W.A. Kretser.	NO_3 is needed for plant growth and is taken up by plants during the growing season. When plants die and leaves decompose, NH_4 is released. NH_4 is then changed into NO_3 through bacterially mediated nitrification.

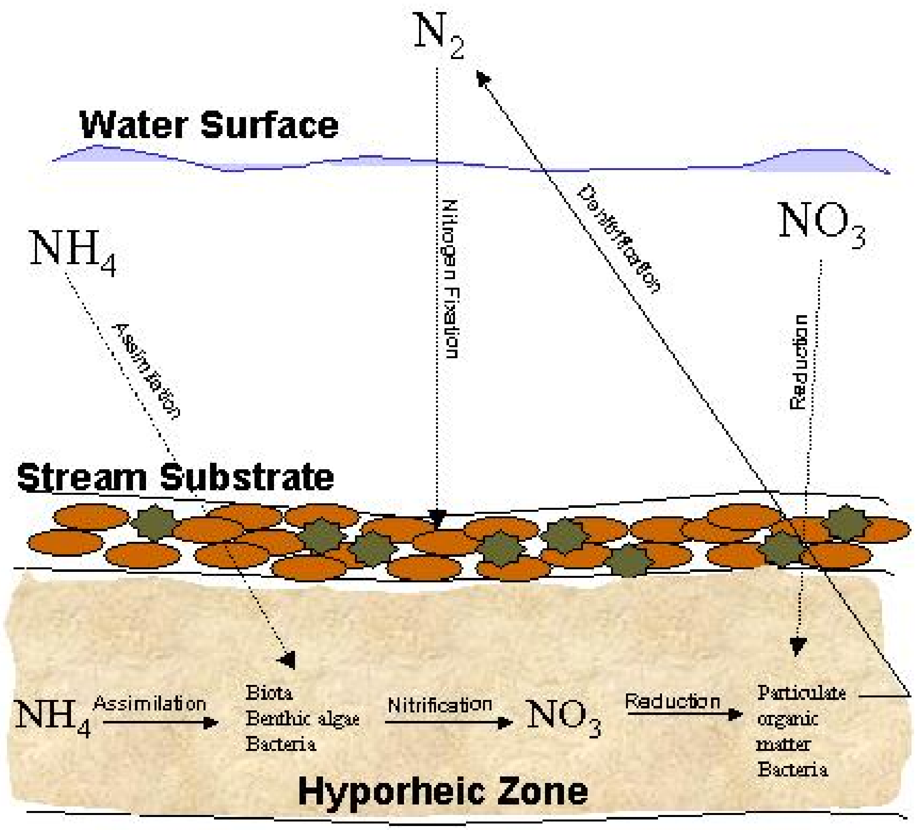

Figure 1: Nitrogen Processing in Streams

2 How have humans altered the availability of nitrogen in the environment?

The N cycle is controlled by natural processes that follow the laws of nature. Humans have little effect on these processes, but do have significant influence on the total input into the system. There is substantial literature regarding the extent and effect of human input into the N cycle. N is a limiting nutrient in ecosystems; without it, plants cannot grow. Natural N cycles allow for N-fixing organisms to assimilate N from the atmosphere, and provide plants and other organisms with the amount of N they need.

Several sources agree that the amount of N fixed in the environment is nearly twice what it should be as a result of human activities. The Ecological Society of America estimates that the amount of natural N fixation on land is approximately 140 teragrams (Tg) per year. Studies identified human activities that contribute to excess N, including:

- The use of fertilizers, farming of legume crops, and burning of fossil fuels, adds an additional 140 Tg of N to land-based ecosystems each year (Ecological Society of America, 1997);
- Forest degradation, with canopy removal and soil disturbances, enhances N loss, especially in N rich soils; and
- Headwater streams are often filled or piped during development. As the number of headwater streams is reduced, more fertilizer reaches downstream rivers.

In the mid-Atlantic region, 43% of the N released into the Chesapeake Bay originates from croplands, 11% from pastures, and 10% from forests (Gardner, R.H., et al, 1996).

The effects of excess N in an ecosystem are well documented in numerous studies, and included:

- The degradation of natural areas and a loss of biodiversity due to invasive species outcompeting native species (Ecological Society of America, 1997); and
- Eutrophication, which causes excess algae to grow, blocking light to the stream, depleting oxygen, and killing fish and other stream organisms.

Author	Summary of Findings
Chesapeake Bay Program and U.S. EPA.	Almost 50% of streamside forests in the Chesapeake Bay watershed have been lost.

Author	Summary of Findings
Ecological Society of America.	The amount of natural N fixation on land is approximately 140 teragrams (Tg) per year. Through the use of fertilizers, farming of legume crops, and burning of fossil fuels, humans add an additional 140 Tg of N to land based ecosystems each year. The amount of N fixed in the environment has increased due to the production of N fertilizers, combustion of fossil fuels, and the farming of N fixing plants such as soybeans and peas. Humans have also caused the release of N from biological storage through burning forests and wood fuels, draining wetlands, and land clearing for agriculture.
Ellis, B.K., J.A. Craft, and J.A. Stanford.	As the percent of logged trees increased, the concentration of NO_3 plus NO_2 N in streams increased proportionately. Logging and road building are also associated with nutrient losses in the watershed. Canopy removal and soil disturbances enhance N loss, especially in N rich soils.
Gardner, R.H., et al.	Pre-1700, 95% of the Chesapeake Bay watershed was covered in forest. By 1840-1900, 40-50% of the land was cleared, with 80% converted to agriculture. 43% of the N released into the Chesapeake Bay originates from croplands, 11% from pastures, and 10% from forests.
Global TechnoScan.	Fertilizer application and fossil fuel burning increase N inputs to streams.
Groffman, P.M., and A. Myers.	Suburban streams have a higher denitrification rate than forested streams, due to the increase in N inputs.
Harris, S.	Excess fertilizer runs into streams, increasing N concentrations.
Kimball, J.W.	Agriculture is responsible for up to 50% of N fixation on earth.
Melillo, J.	Humans have increased concentrations of fixed N through the addition of fertilizers and the burning of fossil fuels. The combustion of coal and oil lead to acid rain and smog. Atmospheric deposition is the largest single source of human-derived N in the eastern U.S. coastal waters. Humans have doubled the amount of fixed N available in the environment. N found in streams and rivers comes from fertilized farmlands, sewage treatment plants, and fossil fuel combustion.

Author	Summary of Findings
Meyer, J.L., et al.	When land is developed, headwater streams are often filled or piped. As the number of headwater streams is reduced, more fertilizer reaches downstream rivers, leading to eutrophication.
Peterson, B.J., et al.	N loading has increased due to fertilizer application, farming of legume crops, disposal of human and animal wastes, and combustion of fossil fuels.
Pidwirny, M.J.	Humans have increased the amount of N and affected the N cycle in many ways through: the application of N fertilizers to crops; atmospheric deposition from the burning of fossil fuels and forest burning; increases in the amount of ammonia from animal wastes due to livestock ranching; and sewage waste and septic tank leaching.
Smith, V.H., G.D. Tilman, and J.C. Nekola.	Humans have nearly doubled the amount of N available in the environment through land transformations, agricultural fertilizers, fossil fuels, etc. Land use, population density, and livestock densities determine the amount of N transported to waterways.
Tank, J.L., et al.	Humans have altered the N cycle by burning fossil fuels, producing fertilizers, and disposing of waste.
Thomas S.A., et al.	Urban areas have the highest rates of N pollution. Fossil fuels, legumes, food, and fuel import may be responsible for more than 90% of N inputs. Industries produce more available N than is fixed by ecosystems.
Triska, F.J., J.H. Duff, and R.F. Avanzino.	Increases in NO_3 are due in part to atmospheric inputs and agricultural fertilizers.
University of Georgia.	Fertilizer application and human and animal waste disposal increase N inputs to streams.
Webster, J.R., et al.	Atmospheric deposition, direct additions of N, and agricultural activities have led to large increases in dissolved inorganic N in stream water.

3 How is nitrogen released to streams?

The effects of excessive N in streams are well-documented (see question 2). It is important to understand how N is released to streams in order to determine how best to control or minimize that release. Literature reviews indicated that streams receive N from their surrounding watersheds and some of that N input is a result of natural sources, including:

- Litterfall, including deciduous leaves, needles, cones, twigs, and bark;
- Nutrient rich precipitation that is captured by leaves before it falls to the ground, or throughfall;
- Lateral movement through soils, or through groundwater; and
- Remineralization;
- Scouring floods; and
- Microbial degradation of bryophytes and wood.

Studies show that plants can only uptake a certain amount of N. When excess N enters a terrestrial ecosystem through atmospheric deposition, precipitation, or groundwater inputs, the system may become “nitrogen saturated” (Peterson et al., 2001). Once an ecosystem has all the N it is able to assimilate, excess N is released to streams, groundwater, and the atmosphere.

Multiple studies indicated that first to fourth order streams have higher removal efficiency than larger streams. For example, in one stream regression model (Seitzinger et al., 2002), 90% of total direct N released from terrestrial ecosystems entered first to fourth order stream reaches. These lower order streams comprise approximately 90% of total stream length in a river system. Additionally, half of the N removed from a river network is removed from first to fourth order streams.

Most sources noted that streams differ in their N concentrations due to varying factors including the demand for N by forest vegetation, hydrologic factors such as storage, and land-use history. As NO_3 concentrations increase in streams, acidity and aluminum concentrations increase, impacting aquatic organisms.

Author	Summary of Findings
Alexander, R.B., R.A. Smith, and G.E. Schwarz.	The proximity of N sources to large streams and rivers influences the amount of N delivered to the Mississippi basin. Larger streams travel thousands of kilometers and still contain 90% of N inputs when they reach coastal waters, versus smaller streams with lengths less than a few hundred kilometers containing less than 40% of original inputs.

Author	Summary of Findings
Bernhardt, E.S., R.O. Hall, Jr., and G.E. Likens.	Natural events, such as an ice storm, which can cause damage to the forest canopy, can result in a higher loss of NO_3 from forest soils, which affects NO_3 concentrations in stream water. The amount of NO_3 imported to the stream is correlated to the rates of nitrification within the stream sediments.
Burns, D.A.	Streams differ in their N concentration due to varying factors including the demand for N by forest vegetation, hydrologic factors such as storage, and land-use history. As terrestrial ecosystems become N saturated, NO_3 concentrations increase in streams, leading to acidity and high aluminum concentrations, which impact aquatic organisms.
Dodds, W.K., et al.	N is released to streams through remineralization, scouring floods, and microbial degradation of bryophytes and wood.
Ecological Society of America.	Plants can only uptake a certain amount of N. Once an ecosystem has all the N it needs, the system reaches "nitrogen saturation" and all excess N is released to streams, groundwater, and the atmosphere.
Hall, Robert O., E.S. Bernhardt, and G.E. Likens.	Streams receive nutrients from terrestrial ecosystems and deliver nutrients downstream.
Hamilton, S.K., et al.	N from industry and agriculture is transported by groundwater flow as NO_3 and is discharged to streams and rivers. Additionally, surface runoff and waste effluents add NH_4.
McMahon, P.B., and J.K. Bohlke.	N enters streams through groundwater inputs.
Mulholland, P.J.	Precipitation and canopy leaching (throughfall) add N and phosphorous to the stream, and soil retains inorganic forms of N.
Peterson, B.J., et al.	N is released to streams through overland flow as terrestrial ecosystems become N saturated.
Pidwirny, M.J.	Because NO_3 is very soluble, it is often lost through the soil and can reach streams by leaching into groundwater.
Seitzinger, S.P., et al.	High N input comes from urban runoff and wastewater treatment facilities. According to the model run in this study, 90% of total direct watershed N loading enters 1st to 4th order stream reaches. Additionally, half of the N removed from a river network is removed from 1st to 4th order streams.

Author	Summary of Findings
Simonin, H.A., and W.A. Kretser.	NO_3 concentrations are often higher during the spring snowmelt, prior to when vegetation actively utilizes nitrate. The impact and export of NO_3 was highest in March. High concentration of NO_3 caused acidity during the spring snowmelt.
Smith, V.H., G.D. Tilman, and J.C. Nekola.	More N is applied to agricultural plants than is needed. This excess N accumulates in soils, migrates to surface waters or groundwater, or enters the atmosphere where it returns to the ground or the ocean. Eutrophication from excess nutrients is responsible for more than 60% of degraded water quality in U.S. rivers.
Tank, J.L., et al.	Most dissolved organic nitrogen (DON) in this study originated from the leaching of leaf litter into forest soils.
Triska, F.J., J.H. Duff, and R.F. Avanzino.	Increased applications of N have contaminated groundwater and increased inputs to surface waters.
Triska, F.J., et al.	Small streams in forested watersheds depend on nutrient inputs from the surrounding environment. Litterfall, including deciduous leaves, needles, cones, twigs, and bark, provide N inputs in the study stream. During autumn, leaves partially decay in the canopy increasing N concentrations. Nutrient rich throughfall also provided a source of N. Debris dams created a large N pool. N also enters streams through groundwater, precipitation as throughfall, or lateral movement through adjacent soils.

4 How is nitrogen processed in streams?

To develop strategies that enhance N sequestration in headwater streams, we have to understand how N is processed in these ecosystems. Small headwater streams make up 85% to 90% of a watershed's drainage network and collect most of the water and dissolved nutrients from surrounding terrestrial ecosystems. Several studies have shown that small, low order streams are most effective in processing N because they are areas with high biological activity and high sediment-water contact time (Hall and Tank, 2003). Small headwater streams can process more than 50% of inorganic N inputs from their watersheds (Peterson et al., 2001).

The literature review reveals that a significant amount of N processing occurs in the hyporheic zone, where surface water and groundwater are interchanged beneath the stream bed. Between 10 and 50% of NO_3 inputs are taken up in the hyporheic zone of streams. Retention of NO_3 has been shown to increase with the size of the hyporheic zone (Harris, 2000).

Several studies conducted in headwater streams around the country have indicated that NH_4 and NO_3 concentrations are affected by a range of processes within the stream: input, nitrification, denitrification, assimilation, ammonification, biological uptake, sorption, and regeneration. NH_4 and NO_3 are input to the stream column through precipitation, groundwater inputs, organic material, and overland flow. Ammonification is a process that releases NH_4 into the water column from the stream bed. In the hyporheic zone, NH_4 is assimilated by biota, benthic algae, and bacteria. These organisms nitrify the NH_4 through aerobic processes, converting it to NO_3. This process leads to a depletion of oxygen. Denitrifying bacteria convert NO_3 to N_2, which is released harmlessly back into the atmosphere. Denitrification, which occurs under anoxic conditions, is considered the most dominant and permanent removal process (Seitzinger et al., 2002). Additionally, N can be fixed through biological uptake by autotrophic and heterotrophic organisms. N can also be sorbed into stream sediments where it remains immobile until it is released back into the stream column.

These processes are all a part of the nutrient cycle within the stream. The distance a nutrient travels along a stream channel before it completes a full cycle is called a nutrient spiral.

Author	Summary of Findings
Bernhardt, E.S.	Nutrients may be retained in the stream, or they may be chemically transformed; inorganic inputs may be changed into organic or particulate exports. Streams also process nutrients through denitrification, leading to significant and permanent losses of NO_3.
Bernhardt, E.S., R.O. Hall, Jr., and G.E. Likens.	Streams are important sites for nutrient transformation and retention. Within the stream, N is converted among inorganic oxidation states, between organic and inorganic forms, and dissolved or particulate forms. NO_3 is both increased through nitrification in streams, and also decreased due to uptake. NH_4 uptake can occur through sorption onto sediments, as well as assimilation by both autotrophic and heterotrophic stream organisms. Some uptake is nitrified, and some is denitrified by bacteria. "It is clear that streams are transforming or even retaining a significant proportion of the N that enters them from the surrounding forest." N is often found to have the highest concentrations in headwaters, and the lowest concentrations at confluences with other streams.
Boulton, A.J., et al.	Ammonification, nitrification, and denitrification occur when water enters the hyporheic zone. These transformations of dissolved N are controlled by oxygen availability. Accumulation of N along a flow path is an indicator of nitrification in the hyporheic zone.
Brookshire, E.N.J., et al.	The hyporheic zone can strongly influence stream retention of dissolved inorganic nitrogen (DIN). [The hyporheic zone is where stream water mixes with groundwater.] Little is known about dissolved organic nitrogen (DON) in the hyporheic zone. DON concentrations were higher in hyporheic zones than in surface water. NH_4 concentrations were higher in hyporheic zones of old growth forest streams than aggrading forests.
Burns, D.A.	Concentrations of N in streams are affected by aquatic uptake and other biogeochemical cycling processes. Also, the mixing of groundwater and stream water (hyporheic zone) affects the transport of nutrients. The dominant processes occurring in the hyporheic zone are denitrification and nitrification, although this zone can also be a storage area. According to this study, denitrification and uptake by epilithic communities were the dominant causes of NO_3 retention. NO_3 increases were attributed to mineralization and nitrification in the hyporheic zone.

Author	Summary of Findings
Environmental Protection Agency (EPA).	The percentage of N reaching the Gulf was lower when the N was carried for an extended time by small streams.
Gardner, R.H., et al.	NO_3 concentrations in streams are dependent on water available for transport, vegetation and microbial uptake, soil moisture, temperature, and precipitation. NO_3 inputs can be seasonal. They are low during the growing season and high during spring snowmelt. N concentrations in streams vary dependent upon water level, season, temperature, and amount of rainfall. It also depends on the physiographic province; greater concentrations of DON were found in streams draining the Appalachian Plateau as compared to the Ridge and Valley province.
Hall, Robert O., E.S. Bernhardt, and G.E. Likens.	Streams alter the form and amount of nutrients through uptake and transformation of dissolved and particulate matter.
Hall, R.O., and J.L. Tank.	Headwater streams remove and transform N quickly because of high biological activity and high sediment-water contact time.
Hamilton, S.K., et al.	N is removed in streams by assimilative uptake of N and bacterial denitrification of NO_3. Bacterial nitrification occurs primarily in biofilms and in the sediments, and requires both oxygen and NH_4. In this study, the majority of N is transformed by nitrification, with the potential for denitrification further downstream.
Harris, S.	10-50% of NO_3 is taken up in the hyporheic zone of streams. Retention of NO_3 increases with the size of the hyporheic zone. The retention of N in the hyporheic zones may be temporary.
Hill, A.R.	Bacterial denitrification in anaerobic sediments removes N from water by reducing NO_3 into N_2 gas.
Holmes, R.M., et al.	Denitrification can remove N from streams through stream bottom and subsurface sediments. The process of nitrification removes N from streamwater and produces nitrous oxide.
Martin, L.A., et al.	Denitrification occurs when bacteria oxidize organic carbon while using NO_3 as an electron acceptor. This produces N_2O and N_2 and removes available N from a system. Denitrification may improve water quality, reducing excess N enrichment. However, excess loss of N can have a negative effect on streams that are N limited.

Author	Summary of Findings
McMahon, P.B., and J.K. Bohlke.	Several processes remove or transform N in streams, including both denitrification and the mixing of surface water and groundwater. NO_3 concentrations can be reduced, or diluted, when high concentrations of NO_3 in groundwater mixes with low concentrations of NO_3 in stream water. This is the area where denitrification takes place.
Mulholland, P.J.	Streams have the ability to retain nutrients, but often lose them during large storm events because of increased flow. Nutrients in streams can be transformed from inorganic forms into dissolved organic or particulate forms.
Mulholland, P.J., et al.	Short uptake rates and residence times for NH_4 indicate that this was a limiting nutrient in the study stream. Uptake rates were dependent on concentration of NH_4 in the water column. Nitrification is an important sink for NH_4 and is a source of NO_3 in streams.
Munn, N.L., and J.L. Meyer.	Uptake length is a "measure of how rapidly an element is removed from the stream water." NO_3 retention is highest in streams with low nitrogen: phosphorus ratios, indicating that N is limited in those streams.
Peterson, B.J., et al.	Small headwater streams make up 85% of a watershed's drainage network and collect most of the water and dissolved nutrients from surrounding terrestrial ecosystems. Studies show that small streams are more effective in processing N than larger streams. Studies found that 70-80% of NH_4 was removed from streams due to uptake on the stream bottom. Approximately 20-30% was removed due to nitrification. Small headwater streams can process more than 50% of inorganic N inputs from their watersheds. NH_4 and NO_3 concentrations are affected by input, nitrification, biological uptake, sorption, and regeneration.
Pidwirny, M.J.	N as NH_4 can be absorbed onto the surfaces of clay particles in the soil.
Seitzinger, S.P., et al.	N is removed from streams through denitrification, organic matter burial in sediments, sediment sorption, and plant and microbial uptake. Denitrification is considered the most dominant and permanent removal process. The three largest "sinks" for N are denitrification in soils, rivers, and river export.
Snyder, D.	The majority of the biological water-cleansing activity in a stream occurs along the bottom. In deforested areas, such as pastures or meadows, a stream is 2 to 5 times narrower than in a forest. Consequently, they have less than 1/4 the bottom surface area.

Author	Summary of Findings
Tank, J.L., et al.	In the fall, NH_4 uptake rates are high, leading to short residence times.
Thomas S.A., et al.	N fixation, nitrification, denitrification, assimilation of ammonium and nitrate and ammonification all occur within streams. Biotic processes transform nutrients and determine when they are exported. N in the water column is fixed and NH_4 and NO_3 are assimilated by biota in the stream bed. Ammonification occurring in the stream bottom releases NH_4 into the water, nitrification converts NH_4 to NO_3, and denitrification converts NO_3 to N_2, which is released into the atmosphere. Nutrient spiraling determines the distances (uptake length) along a stream over which a complete nutrient cycle occurs. A nutrient cycle is the process in which a nutrient is exchanged within various ecosystem compartments such as the water column, stream biota, sediments, etc..
Triska, F.J., J.H. Duff, and R.F. Avanzino.	Denitrification occurs only under anoxic conditions. NH_4 is the common form of N in groundwater with low dissolved oxygen. NO_3 is the common form of N in stream water that is well aerated. Nitrification is an aerobic process, and leads to depletion of oxygen in the hyporheic zone. This process converts NH_4 to NO_3, which is more mobile. Denitrification occurs in anaerobic environments and removes N permanently.
Triska, F.J., et al.	N enters streams through groundwater, precipitation as throughfall, lateral movement through adjacent soils, or litterfall from forest vegetation. Biological inputs of N occur due to fixation on various biological substrates, such as bacteria on wood and moss. N in large particulate organic matter (LPOM) and fine particulate organic matter (FPOM) is processed through physical fragmentation, microbial breakdown, and invertebrate egestion. DON and particulate organic nitrogen (PON) can be released back into the stream, and dissolved inorganic nitrogen (DIN) can be denitrified and removed from the stream.
U.S. Geological Survey.	N is removed from the water in stream sediment through denitrification. Denitrification is the process where NO_3 is converted into harmless N_2 gas by bacteria and vented into the atmosphere.
University of Georgia.	"Small size streams, or headwater streams, may be the most important part of the river system for regulating water chemistry because their large surface to volume ratios favor N uptake and processing."

Author	Summary of Findings
Vallett, M., et al.	Total ecosystem retention is the product of chemical and biological process rates and water residence time. NO_3 consumption occurs more often in areas of slow flow and anoxia. Denitrification is usually suppressed in aerobic systems. Watershed lithology influences the availability of nutrients in water.
Walsh, C.	Most nutrient processing occurs on the bottom or in the sediments of small, shallow streams. Nutrient removal occurs through microbial and plant uptake and diffusion into sediments. However, diffusion from sediments, excretion, and resuspension of sediments release N back into the water.
Webster, J.R., et al.	NH_4 can be transformed to mobile NO_3 by nitrification, through biological uptake, or mineralization. A significant portion of inorganic N input to streams remains in organic form and is transported downstream. Denitrification is the only process that allows for permanent removal of N from streams.
Wollheim, W.M., et al.	In this study, NH_4 added to each stream returned to the water column as soluble, particulate, organic N. The organic N molecule can then be stored in the stream bottom for several weeks until high discharge events export them.

5 What physical and chemical characteristics increase or limit nitrogen removal in streams?

A common theme in all literature regarding N processing in streams is that each stream includes multiple variables. N sequestration studies have identified several physical and chemical characteristics of streams that influence the uptake of N.

Several studies have indicated that smaller, slow moving streams remove greater amounts of N than larger streams because of longer contact times with sediment, benthic detritus, and biofilms. Additionally, many studies indicated that smaller streams have a higher surface to volume ratio, allowing them to process greater amounts of N. Streams with greater depths and higher velocities tend to have longer uptake lengths of both NO_3 and NH_4, because these conditions allow these compounds to travel further distances before they are processed by the stream.

Stream hydrology affects nutrient uptake by influencing biotic characteristics of the stream (see Section 6). For example, increases in transient storage allow for longer water residence times, which increases contact with sediments, and allows for biological uptake by microbes, therefore increasing N uptake (Hall and Tank, 2003). In addition, the depth and velocity of a stream channel influences particulate settling times. The literature did include one study that showed stream size does not affect uptake rates of nutrients. However, the authors suggested that this was the case because they did not study streams with a broad range of sizes (Hall and Tank, 2003).

Geology and geographic area influences water chemistry and stream channel geomorphology, which in turn affect biotic characteristics and nutrient retention. For example, studies noted that streams flowing through forested areas underlain by igneous bedrock may have high phosphorus content. In contrast, streams in the Pacific Northwest or southwest deserts are N limited because of low nitrogen: phosphorus ratios. Geology also influences drainage and topography within a region, which affects stream sediments and the movement of woody debris. These factors all influence nutrient retention (Munn and Meyer, 1990).

Several studies included an examination of how sediment characteristics affect denitrification rates and NH_4 retention. Silt bottom streams have been shown to remove more N than sandy and gravel bottom streams. Denitrification occurs more often in fine-textured sediments because there is less available oxygen, and denitrification is an anaerobic process. NH_4 retention is dependent on sediment sorption and often occurs on the benthic surface (Webster et al., 2003). Sediments with high cation exchange capacity will readily absorb NH_4 (Boulton et al, 1998).

The studies reviewed varied in their conclusions regarding the influence of how light availability and seasonal patterns affected N retention. Light may inhibit denitrification because phototrophic activity adds oxygen to the hyporheic zone and denitrification is an anaerobic process. However, NO_3 uptake has been found to be higher during the day than at night (Burns, 1998). One study indicated that shaded streams have low N uptake in the summer because leaf matter from the previous fall has already decomposed and primary production is limited with the lack of light due to full canopy cover (Hamilton et al., 2001). Denitrification rates have been found to be negatively related to temperature, and are lowest in autumn when dissolved oxygen content (DOC) is highest (Martin et al., 2001). Other studies; however, have shown that the highest removal rates of N occur in the summer with higher temperatures (Hill, 1979, and Holmes et al., 1996) and that there is less demand for dissolved inorganic nitrogen (DIN) by photosynthetic autotrophs when light penetrates the canopy (Mulholland et al., 2000).

Water chemistry, such as the availability of carbon and oxygen, also has an affect on N retention in streams. As NH_4 is released into streamwater, it becomes nitrified and converted to NO_3. Surface/groundwater exchange occurs in the hyporheic zone and allows for denitrification of the NO_3, which converts it to harmless N_2 gas (Alexander, et al., 2000).

Several studies noted that retention of N is also dependent upon the limiting nutrients in a stream. Streams with high NO_3 concentrations will not respond to inputs of NO_3, while nitrification processes will increase in streams limited by NO_3 concentration when NO_3 is added (Martin et al., 2001). In one study, NO_3 retention increased even more when a combination of NO_3 and carbon was added to the stream (Holmes et al., 1996).

Author	**Summary of Findings**
Alexander, R.B., R.A. Smith, and G.E. Schwarz.	Total N loss is inversely proportional to channel size. This is probably due to the influence of channel depth on particulate nitrogen settling times and the supply of nitrate for denitrification. The supply of NO_3 to stream bottom sediments is controlled by the release of N into the water, the nitrification of ammonia (NH_3) supplied by mineralized N, and the exchange of N rich stream water in the hyporheic zone. Oxygen concentrations, stream sediment organic content, depth, and water residence time all affect N loss rates. The study used stream depth as an explanatory variable. It concluded that increases in velocity do not impact the removal rate of N as much as compared to increases in depth.

Author	Summary of Findings
Bernhardt, E.S., R.O. Hall, Jr., and G.E. Likens.	N mineralization and nitrification rates in soils increase with elevation. Concentrations of N in streams vary with forest age and composition, hydrology, soil organic matter content, geomorphology, biotic N demand, rates of instream N transformation, etc. There is a correlation between heterotrophic N uptake and nitrification in a stream when external inputs of NO_3 are high. Seasonal variations, as well as spatial variations, affect N concentrations. The availability of organic carbon limits the uptake of NH_4 and NO_3. Rates of nitrification are limited by the supply of NH_4. Increased concentrations of NO_3 lead to higher nitrification rates. Therefore, NO_3 concentration indirectly influences nitrification rates by mediating the competitive demand for NH_4 between heterotrophs and nitrifiers.
Boulton, A.J., et al.	Exchanges of water, nutrients, and organic matter in the water occur in response to changes in discharge and bed topography and porosity. Sediments with high cation exchange capacity will readily absorb NH_4.
Burns, D.A.	The transformation and uptake of nitrogen in streams is dependent on the duration and intensity of light, substrate grain size, hydraulic gradient, availability of unstable carbon, concentration of nitrogen, and stream velocity. Light may inhibit denitrification because it allows photoautotrophic activity that adds oxygen to the hyporheic zone. However, the study shows that the uptake of NO_3 is greater during the day than at night. The dominant processes of nitrogen removal are dependent on NO_3 supply.
Dodds, W.K., et al.	The longest uptake length coincided with the highest discharge, but was not strongly affected by temperature.
Findlay, S., et al.	Particle size affects the carbon: nitrogen ratio and the presence of microbes (e.g.: wood has higher C:N than fine benthic organic matter [FBOM]).

Author	Summary of Findings
Hall, Robert O., E.S. Bernhardt, and G.E. Likens.	Transient storage is water that is moving slower than the water in the channel. These storage zones may be hyporheic or surface areas. Transient storage may increase nutrient storage although the relationship is weak. In autumn and spring, there was no relationship between NH_4 uptake and transient storage. This may be due to the nature of storage in these streams; there may be side pools rather than hyporheic zones. Nutrient uptake length is the average downstream distance traveled by a nutrient atom before it is removed from the water. Uptake length varies among streams and depends on biological, hydrologic, and geomorphological processes. Increased stream length and velocity lead to increased uptake lengths.
Hall, R.O., and J.L. Tank.	Uptake lengths of NH_4 and NO_3 were not related to stream size. The authors suggested that this was the case because they did not study streams with a broad range of sizes. Physical characteristics only indirectly affect nutrient uptake by influencing biological processes (e.g. increased transient storage increases water residence time, which increases contact time with sediments, and allows for uptake by microbial biofilms). Increased light due to vegetation removal has been linked to NH_4 uptake. Uptake rates from the water column are high in shallow streams. Nitrification rates are increased by the availability of NH_4 and decreased by high labile organic matter availability.
Hamilton, S.K., et al.	Shaded streams may have the lowest N uptake in the summer because leaf litter inputs are decomposed by June and aquatic primary production is limited due to a lack of light. Smaller streams remove greater concentrations of N due to longer water contact times with benthic detritus, sediments, and biofilms. The deeper and faster a stream, the less removal potential is present.
Hill, A.R.	The composition of stream sediments influences N removal rates. A stream with silt rich deposits removed 100-251 mg/m^2 daily as compared to only 20-60 mg/m^2 from streams with sandy and gravel bottoms. The temperature of the stream water can affect the removal rate of N. During the summer months when the temperature was approximately 20ºC, removal rates were highest. In the winter when the temperature was near 0-2ºC, the removal rate was only 20% that of the rate in the summer. At 6ºC, it was 35% and at 10ºC, it was 45% that of the rate at 20ºC.

Author	Summary of Findings
Holmes, R.M., et al.	Temperature of sediments influences denitrification rates. Low rates of denitrification occurred at 10°C, but rates were higher at 24° and 35°C. The substrate can influence the rate of N removal. In gravel-bed streams, surface and subsurface waters mix and subsurface processes influence nutrient supply. In an Arizona stream, most denitrification occurred in bank sediments, not parafluvial or hyporheic sediments. Denitrification was highest where surface water and groundwater mixed. Denitrification occurs under primarily anoxic or hypoxic conditions, and the process requires nitrate to act as an electron acceptor. The addition of NO_3 increased the rate of denitrification, which further increased with the addition of a combination of carbon and nitrate. Denitrification relies on a suitable organic carbon source, sufficient NO_3, and an anoxic or hypoxic environment. Denitrification is primarily limited by N, and secondarily by carbon.
Martin, L.A., et al.	The study stream with naturally high NO_3 did not respond to NO_3 additions. Denitrification increased in the stream with naturally low NO_3 when NO_3 was added. Carbon was not a limiting factor for denitrification in this study. Some studies have shown that denitrification potential is higher in fine-textured sediments where there are anaerobic conditions. Temperature affected the denitrification potential in stream sediments of a mountain stream. The potential for sediment denitrification was mostly related to concentrations of NO_3 in stream water. Where NO_3 concentrations were high, denitrification potential was high and influenced by temperature. Denitrification was higher in sediments of higher elevation streams. Denitrification was negatively related to pH, conductivity, and temperature. Denitrification was generally lower in autumn when DOC was high. Acidic conditions may reduce or inhibit denitrification in stream sediments.
McMahon, P.B., and J.K. Bohlke.	The mixing of groundwater and surface water in a stream increases the amount of time that solutes, such as nitrogen, are in contact with sediments. The increased contact time between sediments and solutes increases the removal rate efficiency. The length of mixing depends on the width of the floodplain. The more narrow the floodplain, the smaller the hyporheic zone and the less mixing occurs. Denitrification can still occur in the winter, during the coldest time of the year.

Author	Summary of Findings
Meyer, J.L., et al.	In small, shallow streams, there is more water in contact with the stream channel; therefore, the distance traveled by a particle is shorter than it would be in larger streams. Wider channels have greater streambed surface area, which allows for more N processing.
Mulholland, P.J.	Concentrations of inorganic N were lower in late autumn, winter, and early spring, and highest in the summer. Most inorganic N uptake in the stream occurred between November and April. Time of day also affects N uptake. Concentrations of N were lowest during the day and highest at night. Soil temperatures are lower in the winter; however, microbial immobilization rates may still be high due to the fresh leaf litter input with a high C:N ratio. Previous studies have indicated that N concentrations in streams are highest in the winter, because of the reduced uptake by terrestrial vegetation and soil microbes. However, this study showed the opposite results, with most N uptake occurring in the winter. This may be due to latitude; previous studies in the northern U.S. and Canada have shown similar results. Stable streamflow and few high stormflows occur in the study area, resulting in greater detritus retention and more stable biological communities, both of which encourage N retention.
Mulholland, P.J., et al.	Low water depth and slow velocity allowed for short uptake lengths and residence time of NH_4. There is less demand for DIN by photosynthetic autotrophs when more light penetrates the canopy. Nitrification of NH_4 and biomass nitrogen on the stream bottom contribute to NO_3 concentrations in the stream.

Author	Summary of Findings
Munn, N.L., and J.L. Meyer.	The retention of nutrients is dependent upon geology, hydrology, and geomorphic structure. Water chemistry and stream channel geomorphology are determined in part by geology. Streams flowing through forested areas underlain by igneous bedrock may have high phosphorus content. In contrast, streams in the Pacific Northwest or southwest deserts are N limited because of low nitrogen: phosphorus ratios. Geology also influences drainage and topography within a region and affects stream sediments and the movement of woody debris. These factors all influence nutrient retention. The study streams vary in parent geology and the size of retention structures such as snags and debris dams. In the western stream, uptake rates were highest (shorter uptake lengths) in stream reaches with debris dams. Uptake rates were lowest in reaches with cobble beds. In the eastern stream, N retention was greatest in gravel stream bottom habitats, due to prolonged surface area contact. The higher the chlorophyll a concentration in the stream, the more NO_3 was retained. Retention decreased as discharge increased. Uptake rate was partially dependent upon the concentration of N.
Peterson, B.J., et al.	Streams with high nitrification rates tended to have higher nitrate concentrations. In headwater streams, N removal occurs mostly in sediments and biofilms covering submerged surfaces. Shallow depths and high surface to volume ratios in smaller streams allow for shorter uptake lengths of N. Stream discharge (related to depth and velocity) primarily determines NH_4 uptake length. As N inputs to streams increase, removal efficiency will be reduced and inorganic N will travel further, leading to eutrophication of rivers, lakes, and estuaries.
Seitzinger, S.P., et al.	Removal of N was compared with many variables including river order, river discharge, land use, N-loading, water residence time, and water displacement. Other factors, such as depth of the water, time of travel, and river network configuration are also considered. The longer water stays in a stream, the more particulate settling occurs. More NO_3 diffuses into sediments, which leads to a higher removal rate of N. N removal decreases as flow and depth increase.
Tank, J.L., et al.	N is dependent upon high quality stream sediments, and an adequate supply of ambient NO_3 concentrations. Uptake length of NH_4 increased over time in the study, from 4 minutes on Day 1 to 15 minutes on Day 42. This could be attributed to increased discharge, water depth, velocity, and lower water temperature.

Author	Summary of Findings
Thomas S.A., et al.	Physical and chemical conditions within hyporheic zones support denitrification. Nutrient retention is related to the exchange of groundwater and surface water. Increasing hyporheic zone size is associated with decreased NO_3 uptake lengths. NO_3 retention increased with decreased oxygen content in the hyporheic zone. Injection of acetate (a labile carbon source) increased respiration rates and enhanced NO_3 consumption.
Triska, F.J., J.H. Duff, and R.F. Avanzino.	High nitrification potential is associated with subchannel sediment. Denitrification was limited in hyporheic zones where there was minimal exchange with surface water. The author speculated that high retention of ammonium in the hyporheic zone was associated with sediment sorption because increases in NO_3 concentrations only accounted for a small proportion of ammonium retention, desorption occurred after cutoff, and subsurface sediments contained clay minerals that sorb NH_4.
Triska, F.J., et al.	Significant losses of N occurred in winter during high discharge. Denitrification is an important process in streams with fine sediment stream bottoms and high NO_3 levels. It may be less important in streams with gravel bottoms and low NO_3 concentrations.
U.S. Geological Survey.	Efficiency is dependent on the amount of time nitrogen travels through small streams. The amount of N removed is dependent on the amount of water in contact with bottom sediments.
Vallett, M., et al.	Hyporheic zones may be sinks or sources of nutrients, depending on the processes occurring in surface and groundwater. Surface and hyporheic water mix, allowing for the exchange of nutrients. Since NO_3 concentrations vary between surface and groundwater, production and consumption of NO_3 may be an aspect of system metabolism in the hyporheic zone. This study suggests that nutrients may be transformed and steep redox gradients may exist near the stream surface in streams with low hydraulic conductivity. Some research has shown that moderate increases in discharge may increase nutrient uptake by increasing nutrient concentrations in sediments. However, significantly higher flows reduce the time that dissolved nutrients in the water interact with benthic sediments, which leads to longer uptake lengths. Uptake length in this study was influenced by stream discharge and velocity. A strong relationship was identified between transient storage and nutrient retention. Other studies indicate that shortest uptake lengths were associated with lowest N:P ratios.

Author	Summary of Findings
Walsh, C.	Denitrification depends on anoxic conditions, and a supply of carbon and NOx. Plant uptake of NOx depends on available habitat, light for photosynthesis, and phosphorus. Denitrification is limited by imperviousness of stream sediments and the connection between stream components.
Webster, J.R., et al.	Processing and transformation of nitrogen occurs in the hyporheic zone. Most NH_4 was taken up on the benthic surface before entering the hyporheic zone. Disturbances in small streams may influence the transport of dissolved inorganic nitrogen downstream. In this study, uptake lengths were affected by discharge and water velocity. NH_4 uptake length was positively related to NH_4 concentration and discharge.
Wollheim, W.M., et al.	Because small streams have high surface to volume ratios, they process greater amounts of N relative to transport. Debris dams increase retention of particulates and organic nutrients. The uptake length of NH_4 increased with increasing discharge (and increased depth and velocity). Study results indicated that NH_4 uptake, DIN, net primary production and respiration, and soluble reactive phosphorus are related. When phosphorus (P) limitation was decreased by adding P to the stream, biological activity was strong enough to counteract high depth and velocity and lowered NH_4 uptake lengths. If nutrient uptake is saturated, increased nutrient concentrations will cause the vertical mass transfer coefficient to decline. As N concentrations increase, nitrification increases.

6. What biological processes increase or limit nitrogen removal in streams?

Numerous studies indicate that biological processes are a vital part of N sequestration in streams. Bacteria in the stream bottom and in the hyporheic zone reduce oxygen, creating an anaerobic zone where denitrification can occur (Boulton et al, 1998). The hyporheic zone must also have sufficient organic matter and a population of microbes for the denitrification process.

Several studies have shown that aquatic macrophytes as well as autotrophic and heterotrophic epilithic communities are partially responsible for N uptake. In streams that receive significant amounts of sunlight, algae are the dominant N consumer. In forested streams, fungi and bacteria retain most of the N inputs (Global Technoscan, 2001). Photoautotrophs and heterotrophs uptake NH_4, while only photoautotrophs remove NO_3. Uptake of carbon by heterotrophic organisms increases the demand for N.

NH_4 can also be converted to NO_3 by nitrifying bacteria. Nitrosomonas bacteria oxidize ammonia (NH_3) to NO_2. Nitrobacter bacteria oxidize the NO_2 to NO_3. Other bacteria that live deep in aquatic sediments are also involved with the denitrification process. They uptake NO_3, use the oxygen, and release the N as harmless N_2 gas (Kimball, 2003).

Studies have shown that fine benthic organic matter (FBOM), epilithon, wood, and decaying leaves also account for significant retention of N. Streams with high biological demand, decomposing leaves, and large plant and microbial biomass have short NH_4 uptake lengths. NH_4 is processed much quicker than NO_3 in streams because it requires less energy for uptake. NO_3 concentrations are higher when the biological demand for N is met by NH_4 concentrations in the stream. Moss covered rock provides a stable substrate for microbial processes. High NO_3 retention occurs in these components of the ecosystem, most likely due to higher respiration rates (Munn and Meyer, 1990).

Author	**Summary of Findings**
Alexander, R.B., R.A. Smith, and G.E. Schwarz.	Benthic denitrification is the dominant loss process in streams.
Bernhardt, E.S.	Studies show that nutrient retention is closely tied to the quality of organic material in the stream. N may limit autotrophic production. There is considerable seasonal variation in stream NO_3 levels. N levels can vary from at or below detection limits during the growing season to a peak at spring snowmelt.
Boulton, A.J., et al.	Bacterial activity may reduce oxygen, allowing for anaerobic processes such as denitrification to occur. The hyporheic zone regenerates inorganic N, which may later be used in biotic uptake. Upwelling water from the hyporheic zone may contain nutrients that promote algal growth.

Author	Summary of Findings
Burns, D.A.	Aquatic macrophytes and autotrophic and heterotrophic epilithic communities are responsible for partial N uptake. Photoautotrophs have a significant impact on N concentrations, resulting in concentrations of NO_3 to be highest in the early morning before sunrise and lowest during the late afternoon. N concentrations in streams increase after storm events, but then a rapid uptake by the periphyton community can occur due to new growth from scouring tissues from surfaces.
Dodds, W.K., et al.	No relationship between N turnover rate and the growth of invertebrates were found in this study. Adult insects leave the stream to reproduce, and take their store of N with them. Primary consumers digested 67% of the inorganic N from benthic algae and microbes, whereas predators acquired 23% from the consumers. Most N in the stream was retained by fine benthic matter, bryophytes, and epilithon.
Findlay, S., et al.	Ergosterol, a fungal sterol, concentrations in a stream were positively associated with the substrate C:N ratio. Bacterial concentrations were negatively correlated with C:N. No patterns were observed between bacteria or fungi and DIN. The availability of DIN influences microbial communities.
Global TechnoScan.	Plant life (algae) uses N in sunny streams, and fungi and bacteria are key players in forested streams.
Groffman, P.M., and A. Myers.	Hyporheic zones need a sufficient amount of organic matter and must be able to support a population of microbes in order for denitrification to take place. Stream features with a high organic matter content have a higher rate of denitrification. Studies have shown that increasing the size of transient storage zones may increase nutrient uptake.
Hall, R.O., and J.L. Tank.	The authors hypothesized that highly productive streams should transform N at higher rates. Uptake of carbon by heterotrophs increases demand for N. Gross primary production (sum of net primary production and respiration) predicted NO_3 uptake velocities. High GPP can lead to input of algal derived organic matter, which could decrease nitrification. N uptake by autotrophs and heterotrophs is the primary cause of N removal from streams. Photoautotrophs and heterotrophs remove NH_4 while only photoautotrophs remove NO_3. Nitrification was low in these study streams because of low NH_4 concentrations and high demand by heterotrophs. No studies have shown what factors affect N uptake aside from geomorphic features, such as water velocity and depth. Physical attributes only indirectly control uptake, biotic demand from algae and microbes in biofilms will determine N uptake and transformation. Researchers assumed that denitrification rates in these study streams were low and limited by NO_3 and carbon availability and anoxic conditions.

Author	Summary of Findings
Hamilton, S.K., et al.	The addition of NH_4 to a stream system can be removed by autotrophic or heterotrophic organisms, transformed by nitrifying bacteria to NO_3, or just flow downstream. Epilithon, FBOM, wood and leaves accounted for 97% of the N retained in the study reach. Epilithon that was attached to cobble was determined to be the most N-enriched compartment.
Harris, S.	"The few centimeters of sediment in small streams are a habitat for bacteria and fungi, which may be using the nitrogen" -Thomas. Bacteria use NO_3 for respiration (denitrification) and turn it into N_2 gas.
Hill, A.R.	Approximately 15% of NO_3 is removed from water by benthic algae and macrophytes.
Holmes, R.M., et al.	Most denitrifying bacteria are facultative anaerobes, which can survive in both aerobic and anoxic conditions. In some streams, the loss of N by denitrification can "strongly influence primary productivity." When too much N is lost, it limits growth.
Kimball, J.W.	Certain bacteria in the soil can fix nitrogen in streams. Bacteria of the genus Nitrosomonas oxidize NH_3 to nitrites. Bacteria of the genus Nitrobacter oxidize NO_2 to NO_3. These are nitrifying bacteria and supply N to the roots of plants. Bacteria that live deep in soil and aquatic sediments are also responsible for the process of denitrification. They use NO_3 as oxygen and NO_3 is transformed into nitrogen gas.
Meyer, J.L., et al.	Bacteria, fungi, and microorganisms in the streambed consume nitrogen compounds and convert it into less harmless forms.
Mulholland, P.J.	Studies have shown that limiting nutrients are taken up in the stream primarily by microbes, and secondarily by algae. N in streams rely on terrestrial detritus inputs and the subsequent decomposition by stream microbes. Uptake by stream autotrophs occurs during periods of high light. Light is a limiting factor for periphyton growth, and as light levels decline with leaf emergence in late spring, net retention of N also declines rapidly. Denitrification is a permanent N removal process.

Author	Summary of Findings
Mulholland, P.J., et al.	The liverwort Porella pinnata, decomposing leaves, and FBOM were responsible for the highest uptakes of NH_4. Epilithon and bryophytes accounted for 31% of the total NH_4 uptake rate. Nitrification was responsible for most of the NH_4 uptake in the stream. High biological demand, decomposing leaves, and large plant and microbial biomass resulted in short uptake lengths for NH_4. NO_3 provided 65-78% of the nitrogen needed by bryophytes and epilithon. The study showed that nitrate is controlled by the biological demand for N and the availability of NH_4 to meet that demand. Aquatic vegetation and seasonal changes in gross primary production impact nitrate much more than NH_4. Bryophytes may be significant for long-term nutrient retention in streams.
Munn, N.L., and J.L. Meyer.	N fixing bacteria attached to woody debris play an important role in the decomposition of wood in northwestern streams. Because N uptake was higher in untreated sediments, as compared to laboratory sterilized sediments, scientists could conclude that biotic processes maintain low NH_4 concentrations in streams. Microbial processes were found to maintain low NH_4 concentrations in both study streams. Moss covered rock outcrops formed a stable substrate, and resulted in high NO_3 retention in the eastern stream, possibly due to higher respiration rates. The study showed that biotic control and the demand for N lead to shorter N uptake lengths.
Peterson, B.J., et al.	NO_3 uptake occurred through biological assimilation and denitrification. NH_4 is removed from water through photosynthetic organisms such as unicellular algae, filamentous algae, and bryophytes. Heterotrophic organisms such as bacteria and fungi also uptake NH_4 in water. These organisms become a food source for fish and macroinvertebrates. Decomposed matter deposits on the stream bottom where denitrifying bacteria convert NO_3 to N_2 gas which is released to the atmosphere.
Pidwirny, M.J.	Bacteria, actinomycetes, and fungi are decomposers who live in the upper layer of soil and transform NH_3 to NH_4 salts (mineralization). The autotrophic bacteria Nitrosomonas convert NH_4 to NO_2 and then Nitrobacter bacteria converts NO_2 into NO_3 (nitrification). Denitrification occurs by heterotrophic bacteria converting NO_3 into N_2 or N_2O gas.
Smith, V.H., G.D. Tilman, and J.C. Nekola.	The amount of available N affects the growth of aquatic plants.
Snyder, D.	Most stream removal is the result of biological activity by bacteria in the silt and sediment layer on the stream bottom. When rain water filters through leaf litter in a watershed, it picks up carbon, a food source for bacteria that remove N from stream water.

Author	Summary of Findings
Tank, J.L., et al.	Fine benthic organic matter (FBOM) and leaves represented over 90% of the total N standing stocks in the study stream. All compartments in the food web accounted for approximately 12% of total N tracer added. The nine largest biomass compartments within the study reach included leaves, wood, seston, FBOM, epilithon, moss, macroinvertebrates, salamanders, and fish. The large standing stock of leaves due to autumn leafall accounted for most of the nitrogen tracer retention due to the colonization of microbes. Leaves also had the highest uptake rate of NH_4. Because there was a small standing stock of epilithon and grazers they only accounted for a small amount of N uptake in the study stream.
Thomas S.A., et al.	NO_3 is highly mobile and does not adsorb easily to stream sediments, therefore, retention is due primarily to biotic processes of assimilation and transformation. Autotrophs such as benthic algal communities, coarse particulate organic matter such as leaves and woody debris, fine particulate organic matter and DOC contribute to nutrient retention. These components are regulated by canopy cover (light and leafall) and the process of organic matter by macroinvertebrates. Microbial activity also influences nutrient retention.
Triska, F.J., J.H. Duff, and R.F. Avanzino.	Sediment treated with a nitrification inhibitor or poison lacked nitrate production, indicating that NH_4 in the hyporheic zone may be transformed by stream biota. DIN uptake by stream biota is a temporary sink, and the DIN will eventually be recycled metabolically or through decomposition.
Walsh, C.	Microbial processes in the sediments and surface biofilms transform N. Denitrification is the microbial transformation of NO_3 to N_2 gas, which removes N from aquatic systems.
Webster, J.R., et al.	N retention is dominated by autotrophic and heterotrophic metabolism. Heterotrophic bacteria and fungi immobilize inorganic N. DIN uptake can be dominated by heterotrophic activity. Uptake of DIN is related to the amount of leaf matter in a stream. Epilithic algae and detrital microbes accounted for most of the N uptake.

7 What is the efficiency of nitrogen removal within streams?

It is important to understand the efficiency of N removal in streams in order to determine how to restore streams to process N even more efficiently. The efficiency of N removal is dependent upon physical and chemical characteristics of the stream as well as the biological processes that occur within the stream and the hyporheic zone. Uptake lengths of both NH_4 and NO_3 can range from a few meters to a few kilometers.

In headwater streams, low to moderate amounts of inorganic N can be processed within minutes to hours (Peterson, et al., 2001). A stream regression model run by Seitzinger et al., showed that 37% to 76% of N input to rivers is removed during transport through the river network. First through fourth order streams, which make up approximately 90% of a river network, can remove up to half of the N inputs from the watershed. The model showed that 20% to 25% of N inputs were removed from a first order stream as opposed to 5% from a seventh to eighth order stream (Seitzinger et al., 2002).

Several studies have shown that significant amounts of N are removed from streams in the hyporheic zone. One study showed that the mixing of surface and groundwater can reduce 65% to 90% of NO_3 (McMahon and Bohlke, 1996). Another study showed that 53% of the available NO_3 injected into the study stream was consumed in the hyporheic zone (Vallett, et al., 1996). The dominant removal process for N is denitrification. Bernhardt's study showed that approximately 25% to 100% of NO_3 was removed from a study stream by denitrification (Bernhardt, 2003).

Watershed characteristics can also affect the efficiency of N removal. For example, eight to nine times more N may be removed from a forested stream than from open, non-forested streams (Snyder, 2003). Forested streams are between 2 and 5 times wider than non-forested streams; therefore, these streams have a larger bottom surface area, which allows for increased biological activity in the stream sediments and greater N retention. Additionally, water that leaches through the forest canopy and leaf litter picks up carbon, which is a food source for the bacteria that uptake N. Riparian forest buffers can reduce 30-90% of nutrients and sediments.

Studies have identified various biological organisms that uptake differing amounts of inorganic N. The Dodds study showed that primary consumers digested 67% of the inorganic N from benthic algae and microbes, whereas predators acquired 23% from the primary consumers (Dodds et al., 2000). In another study, leaves accounted for 76% of N uptake and fine benthic organic matter (FBOM) accounted for 9% (Tank et al., 2000).

Author	**Summary of Findings**
Alexander, R.B., R.A. Smith, and G.E. Schwarz.	Small streams removed N at a rate percent water travel time of 0.45 per day as compared to only 0.005 per day in the Mississippi River.

Author	Summary of Findings
Bernhardt, E.S.	Laboratory denitrification assays show that denitrification can remove as much as 25% to 100% of NO_3 from the water in the sediments of the study reach.
Bernhardt, E.S., R.O. Hall, Jr., and G.E. Likens.	With the addition of NH_4, some streams nitrified 100% of the addition, and other streams did not nitrify any. Only 5 of the 17 streams had more NO_3 production than uptake. In several cases, more NO_3 was removed from the water than was exported from the watershed. NO_3 uptake is usually more than NH_4 uptake because there is between 10 and 1,000 times more NO_3 available. "It is clear that streams are transforming or even retaining a significant proportion of the N that enters them from the surrounding forest." N is often found to have highest concentrations in the headwaters, and lowest at confluences with other streams.
Chesapeake Bay Program, and U.S. EPA.	Riparian forest buffers can reduce 30-90% of nutrients and sediments.
Dodds, W.K., et al.	Primary consumers digested 67% of the inorganic N from benthic algae and microbes, whereas predators acquired 23% from the consumers. 23% of the original 309mg of N added into the 210-m stream reach was retained. Less than 1% of the N addition was exported in dissolved nutrient form, the majority left in particulate form. Comparatively, other studies retained 33-48% of N with 25% exported as inorganic nutrients, and 12% retained with 30% exported.
Environmental Protection Agency (EPA).	There is a lack of information on the rates at which N is naturally removed by denitrification and other processes in rivers.
Global TechnoScan.	Streams can remove "as much as 50 percent of the inorganic nitrogen."
Hall, Robert O., E.S. Bernhardt, and G.E. Likens.	Uptake length for NH_4 ranged from 5 to 277 meters in the study stream.
Hamilton, S.K., et al.	Concentrations of NH_4 and NO_3 decreased "considerably" along the reach. Within the 461-m study reach, after adding NH_4 for 42 days, 6.7% of the total added N was retained in the stream. Nitrification was the process responsible for 29-48% of the total NH_4 uptake.

Author	Summary of Findings
Hill, A.R.	Denitrification can remove 6-7% of the annual export of total nitrogen from a river basin. Different streams are more efficient at N removal, removal rates in these study streams vary from 1.7kg to 20.3kg of nitrate over 18 days. In this study approximately 7,300 kg of NO_3 was lost from the system in a year. Approximately 80% of annual N exports occur between November and April when denitrification is lowest.
Holmes, R.M., et al.	"Denitrification decreases by about 40% the amount of continentally derived, river borne nitrogen transported to the oceans." -Seitzinger. Denitrification consumed 5-40% of the NO_3 formed by nitrification in this study.
McMahon, P.B., and J.K. Bohlke.	In the hyporheic zone, 65-90% of the NO_3 concentration can be decreased due to mixing. Mixing, combined with the rate of denitrification, can cause an 80-100% decrease in median NO_3 concentrations. Denitrification alone can account for a 15-30% decrease in NO_3 concentrations.
Meyer, J.L., et al.	One previous study indicated that NH_4 generally traveled less than 65 feet in headwater streams. Another study showed that 64% of inorganic N inputs in headwater streams are transformed within 1,000 yards.
Mulholland, P.J.	Nutrient concentrations in stream water are lower than groundwater inputs, suggesting that instream processes are important in nutrient removal.
Mulholland, P.J., et al.	Approximately 20% of the NH_4 added on day zero was nitrified. NO_3 uptake rates ranged from 0 to 29 micrograms per square meter per minute. Uptake lengths of NO_3 ranged from 101 meters on day zero to infinity on day 20. Uptake lengths for NO_3 were much longer than for NH_4. NH_4 requires less energy for assimilation. Because NH_4 concentrations are generally low in streams, NO_3 is required to meet nitrogen demand.
Munn, N.L., and J.L. Meyer.	NH_4 uptakes rates were greater than NO_3 uptake rates in the surveyed streams. NH_4 is easier than NO_3 to assimilate biotically.

Author	Summary of Findings
Peterson, B.J., et al.	The uptake rate of NO_3 and NH_4 was similar in each of the study streams. NH_4 entering stream water is removed rapidly by biological assimilation, sorption, and nitrification. NO_3 inputs are generally higher than NH_4 inputs and are removed less efficiently. NH_4 and NO_3 sequestered on the stream bottom are released back into stream water over periods of weeks or months. Low to moderate amounts of inorganic N released to headwater streams can be processed within minutes to hours and within a few tens to hundreds of meters. In larger streams, the time required for N processing increases with depth.
Seitzinger, S.P., et al.	According to a stream regression model, 37-76% of N input to rivers is removed during transport through the river network, 60% on average. Half of that is removed in first through fourth order streams, which make up 90% of total stream length. 20-25% of N input was removed from a first order stream, as compared to only 5% removal from a seventh or eighth order stream. However, the total mass of N removed per meter of stream increases as the stream order increases. This is because larger amounts of N are input in larger streams and a large amount is removed, but it is a smaller percentage of N inputs. 60-70% of the direct watershed nitrogen input to first through fifth order streams is removed within the river network.
Simonin, H.A., and W.A. Kretser.	The study showed that the amount of NO_3 that entered stream water from the watershed exceeded the amount that fell as nitrate deposition. The study did not account for dry deposition to the watershed, nor the mineralization of N from the forest floor. Concentrations of NO_3 were highest in the spring, 3-4 times greater than in the summer.
Snyder, D.	Eight to nine times more N is removed from a forested stream than from open, non-forested streams.
Tank, J.L., et al.	NO_3 uptake length was three times higher than ammonium uptake. The nine major compartments of the food web only retained 12.3% of the added N tracer after 42 days. Leaves accounted for 76% and FBOM accounted for 9% of that retention. The study can only account for 53% of the added N tracer. The missing N tracer could be attributed to uptake, retention, and loss through microbial processes in the hyporheic zone; denitrification; nitrification; and an underestimation of the standing stocks of organic matter.
U.S. Geological Survey.	Rates of N reaching the Gulf of Mexico from large rivers are much higher than from small streams.

Author	Summary of Findings
University of Georgia.	Small streams take up the most inorganic N. They also remove some NO_3, but not as efficiently.
Vallett, M, et al.	The study showed that 53% of the available NO_3 injected into the stream was consumed in the hyporheic zone. Uptake lengths ranged from 133 meters at baseflow to greater than 3km during spring runoff.
Webster, J.R., et al.	Uptake length for NH_4 in this study ranged from 14 meters to 1.3 kilometers.
Wollheim, W.M., et al.	NH_4 uptake length in this study ranged from 40 meters to 5,360 meters.

8 How can existing streams be enhanced to promote greater nitrogen sequestration?

Scientists are currently studying the processes that control N uptake, retention, and spiraling within stream ecosystems. Few studies conclude with specific strategies as to how streams can be enhanced to promote greater N sequestration. Studying the geomorphology, water quality, and biological and habitat characteristics of unimpacted streams can provide information for future studies.

Peterson's study suggests that management strategies should focus on restoration and preservation of small stream ecosystems, which are threatened with diversion and channelization (Peterson et al., 2001). Several studies have indicated that small streams, including headwater streams, are the most efficient at retaining N because they are shallow, with slower velocities, and higher volumes of transient storage. Each of these characteristics allows for particulate settling, which promotes the uptake of NO_3 and NH_4 from biota in the stream bed and the hyporheic zone.

Based on the literature review, stream restoration activities that create natural bottom streams that allow for the mixing of surface and groundwater, improved habitat for benthic organisms, and pools that slow water velocity should promote uptake of NO_3 and NH_4. Each of these ecosystem components has been shown to be important in the processing of N in streams. Improving water quality and therefore promoting greater abundance and diversity of benthic organisms is particularly important because denitrification is a biologically driven process.

Triska's studies indicate that buffer strips, retention ponds, and channel reconstruction can be used to enhance NO_3 retention. Success of these restoration projects depends on the structure and permeability of soil, hydraulic head, and precipitation pattern, which affect nutrient transport. Biotic processes involved with nutrient retention are dependent upon dissolved inorganic N and oxygen concentration, temperature, N-cycling rate, and the availability of dissolved and particulate organic carbon. Effective management of restoration activities requires long term studies that experiment with various physical, chemical and biological parameters to determine how best to maximize N retention (Triska et al., 1993).

Several studies have also shown that forested buffers enhance N sequestration in streams. Enhancing stream buffers provides benefits such as increased leaf litter that provide food for fish and aquatic organisms; fish/wildlife habitat; nutrient retention in woody vegetation and through denitrification processes; and the filtering of runoff, which slows water velocity (Chesapeake Bay Program and US EPA, 1999). Because stream buffers are effective at retaining N, the USDA partners with states to provide landowners compensation for planting buffer areas along open streams through the Conservation Reserve Enhancement Program (CREP).

Author	Summary of Findings
Chesapeake Bay Program and U.S. EPA.	Enhancing stream buffers provides benefits such as: leaf food for fish and aquatic organisms, when falling into the stream; fish/wildlife habitat; nutrient uptake- stored in woody vegetation and through denitrification; canopy/shade- keeps water cool and full of dissolved oxygen; and filtering runoff- slows water velocity- infiltration in buffers is 10-15 times higher than grass turf and 40 times higher than a plowed field.
Groffman, P.M., and A. Myers.	Studies have shown that increasing the size of transient storage zones may increase nutrient uptake.
Peterson, B.J., et al.	Management strategies should focus on restoration and preservation of small stream ecosystems, which are threatened with diversion and channelization.
Simonin, H.A., and W.A. Kretser.	The seasonal nature of NO_3 impacts need to be kept in consideration. "A program which would cap NOx emissions and permit allowance credit trading within a specific state or region could be an equitable approach if all the sources which impact the Adirondacks are included." Reducing NO_3 levels would improve pH.
Snyder, D.	The Conservation Reserve Enhancement Program (CREP), is a joint program between states and the USDA that provides landowners compensation for planting buffer areas along open streams.
Tank, J.L., et al.	Little is known about the processes controlling N uptake, retention, and spiraling within stream ecosystems. Quantifying unimpacted streams can provide information for future studies.
Triska, F.J., J.H. Duff, and R.F. Avanzino.	Buffer strips, retention ponds, and channel reconstruction can be used to enhance NO_3 retention, but require a careful balance between the transport of nutrients and biological transformation processes. The structure and permeability of soil, hydraulic head, and precipitation pattern all affect nutrient transport. Biotic transformation is related to DIN and oxygen concentration, temperature, N-cycling rate, and the availability of dissolved and particulate organic carbon. Effective management of restoration activities requires long term studies that experiment with various physical, chemical and biological parameters to determine how best to maximize N retention.
Walsh, C.	Improve urban land design and drainage systems. Use community composition to indicate the state of in-stream nutrient processes.

9 How can design goals be developed? Summary of further research questions.

The literature reviewed for this study indicates that various physical, chemical and biological parameters influence N sequestration. Stream restoration activities have the potential to maximize N sequestration by creating conditions that parallel efficient natural processes.

Baseline studies conducted prior to restoration, as well as at regular intervals after restoration is complete, will provide a growing body of information of these processes and the potential for stream restoration to address excessive N in the environment. Biological and habitat assessments would provide information regarding biological abundance and diversity; instream habitat characteristics such as debris dams, sediment types, logs/snags; hydrology characteristics such as velocity and flow regime; and stream stability. Water quality analysis would provide data regarding physical and chemical parameters, such as pH, temperature, and NO_3 and NH_4 concentrations.

As the literature suggests, each of these parameters could play a vital role in N sequestration in headwater streams. Ongoing studies could answer questions such as:

- Which benthic organisms play a role in N uptake?
- Does a restored stream channel with an increased width and greater surface/subsurface interchange allow for greater N sequestration in the hyporheic zone?
- Would enhanced riparian buffer zones increase the removal efficiency due to greater availability of organic matter, increased carbon inputs, reduced light influences, etc.?
- Do streams with natural bed channels allow for greater sediment contact time, allowing for N uptake?
- Is there a difference between forested streams versus open water systems in terms of removal efficiency?

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