Trends in stream nitrogen concentrations for forested reference catchments across the USA

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Abstract
To examine whether stream nitrogen concentrations in forested reference catchments have changed over time and if patterns were consistent across the USA, we synthesized up to 44 yr of data collected from 22 catchments at seven USDA Forest Service Experimental Forests. Trends in stream nitrogen presented high spatial variability both among catchments at a site and among sites across the USA. We found both increasing and decreasing trends in monthly flow-weighted stream nitrate and ammonium concentrations. At a subset of the catchments, we found that the length and period of analysis influenced whether trends were positive, negative or non-significant. Trends also differed among neighboring catchments within several Experimental Forests, suggesting the importance of catchment-specific factors in determining nutrient exports. Over the longest time periods, trends were more consistent among catchments within sites, although there are fewer long-term records for analysis. These findings highlight the critical value of long-term, uninterrupted stream chemistry monitoring at a network of sites across the USA to elucidate patterns of change in nutrient concentrations at minimally disturbed forested sites.

Keywords: nitrate, ammonium, trends, stream, forested catchment, reference catchments

Online supplementary data available from stacks.iop.org/ERL/8/014039/mmedia

1. Introduction
Human alteration of the nitrogen (N) cycle is a major environmental issue that crosses spatial scales from the
catchment to the globe. Energy and food production have led to a ten-fold increase in reactive forms of N in terrestrial ecosystems from 1860 to 2005 (Galloway et al. 2008). Reactive N is routed to freshwaters through surface runoff and groundwater discharge or atmospheric deposition, resulting in alteration of the forms and concentrations of N species, which may result in aquatic eutrophication and altered stream functions (Stoddard 1994). Despite the implementation of the Clean Water Act (1972) and the Clean Air Act (1970), stream and groundwater N concentrations have continued to increase in large areas of the USA during recent decades (Smith et al. 1987, Lettenmaier et al. 1991, Rupert 2008, Sprague et al. 2011) and have been predicted to further increase in the future (Howarth et al. 2002). However, much of what is known about temporal changes in stream water quality originates from studies where catchments have been altered by land use and land cover change.

In contrast, we know little about temporal trends in N dynamics at forested, headwater streams with minimal human impacts, even though they serve as a benchmark against which we can evaluate more heavily human-modified catchments. Trends in stream-water nutrients in the relative absence of changes in land use or land cover can be evaluated using long-term data from unmanaged forested headwater (i.e., reference) catchments, such as those in the USDA Forest Service Experimental Forests and Ranges (EFR) network. These datasets represent the most complete information available on stream N concentration for reference sites because of their length (e.g., Hubbard Brook Experimental Forest, HJ Andrews and Coweeta Hydrologic Laboratory have been analyzing stream chemistry since 1963, 1969, and 1972 respectively), because of their sampling frequency (i.e., at least biweekly for all sites except HJ Andrews where they collect three-weekly composite samples), and finally because of their spatial coverage (EFRs encompass a suite of climates and forest types across the USA). Data from these reference catchments are frequently used in paired watershed comparisons to evaluate effects of land use treatments, assuming that in the absence of the perturbation under study, both the reference and treatment catchments would behave similarly.

Although stream chemistry trends in reference catchments have been investigated at individual EFRs, a comparison of trends in reference sites across the country has not occurred. Researchers at both Coweeta Hydrologic Laboratory in North Carolina (Swank and Vose 1997) and Fernow Experimental Forest in West Virginia (Peterjohn et al. 1996) observed increased stream N over the last decades in reference catchments and attributed the trend to higher N deposition, and changes in nutrient demand and forest succession within catchments. At the Hubbard Brook Experimental Forest in New Hampshire, stream nitrate concentrations have been declining in recent decades after increasing from 1963 into the 1970s (Likens and Bormann 1995, Campbell et al. 2007). These trends in stream nitrate at Hubbard Brook have not been explained by changes in atmospheric deposition and are thought to be due in part to the long-lasting effect of forest cutting in the early 1900s combined with effects of changing climate (Bernal et al. 2012).

Further, little is known about the synchrony of trends among adjacent catchments within EFRs. Our study fills this gap by analyzing trends in stream nitrate (NO$_3$–N) and ammonium (NH$_4$–N) concentrations from forested reference catchments in multiple EFRs across the USA. To evaluate if stream N trends were synchronous with trends in likely drivers, we examined correlations between trends in stream N, streamflow, and ammonium and nitrate concentration in atmospheric wet deposition.

2. Methods

We analyzed stream inorganic N from 22 independent forested reference catchments in seven EFRs across the continental USA and Puerto Rico (figure 1(a)); these span a wide range of climatic, hydrologic and vegetation conditions (table S1 available at stacks.iop.org/ERL/8/014039/mmedia). Each catchment had a minimum of 12 yr of consistent, high frequency stream chemistry data, daily streamflow data, and weekly wet deposition chemistry collected nearby. These catchments are considered reference because they have not experienced direct anthropogenic disturbances other than atmospheric deposition during the last 60 yr. A total of 559 yr of stream nitrate and 523 yr of stream ammonium data collected at least biweekly were analyzed.

Trends were analyzed using the Seasonal Kendall test (Hirsch et al. 1982). This non-parametric, rank test has been proven robust in evaluating trends in time series that have strong seasonality. We selected this test because, in comparison to other trend analysis methods (e.g., linear regression, time series analysis, etc), the Seasonal Kendall test does not make assumptions about the distribution of the data and allows missing values and censored data without biasing the analysis (Helsel 2005). The Seasonal Kendall test is an extension of the Mann–Kendall test for monotonic trends (Mann 1945). If $(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$ are observations where $X$ is time and $Y$ is the object variable, the Kendall S statistic can be computed from each data pair as:

$$S = P - N$$

where $P$ is the number of $Y_i < Y_j$ for all $i < j$ and $N$ is the number of $Y_i > Y_j$ for $i < j$.

$S$ has a mean of zero and variance:

$$\sigma^2 = \frac{n(n - 1)(2n + 5)}{18} - \frac{\sum(t^2 - 3)}{2(2t - 5)}$$

where $t$ is the number of data pairs involved at any given time. All observations below the detection limit are considered tied, and the differences of all tied pairs are zero. The Seasonal Kendall accounts for the effects of seasonality on trends by combining the Mann–Kendall test computed on each of the seasons separately (Hirsch et al. 1982). Seasonal Kendall tau ranges between $-1$ and $+1$ and is the ratio of the number of positive differences minus the number of negative differences to the number of pairs (discounted for ties). If there is enough disparity between the number of positive and negative differences, then tau is statistically significant.

We analyzed trends in monthly flow-weighted concentrations of nitrate and ammonium in streams, monthly
Figure 1. (a) Locations of the Experimental Forests included in this study; averages from 1996 to 2007 are shown for (b) mean monthly flow-weighted stream nitrate concentration, (c) mean annual streamflow, and (d) mean monthly flow-weighted stream ammonium concentration in study catchments. Error bars are standard deviations of the mean. Horizontal black lines in (b) and (d) indicate minimum detection limits. The mean and standard deviation were calculated from censored values after replacing all values below detection limit by half of the maximum detection limit observed per site between 1996 and 2007.

To evaluate more fully the influence of the length and period of the data record on trend detection, we conducted additional analyses on stream N concentrations from HJ Andrews and Hubbard Brook catchments. After analyzing trends for a minimum period (1996–2007), we iteratively reanalyzed trends after increasing the length of record in 1 yr increments for the full data record (1969–2007 for HJ Andrews, 1964–2007 for Hubbard Brook).

To understand how trends in stream N relate to trends in streamflow or to trends in N in wet deposition at a national level, we performed correlation analyses (Kendall’s tau) between the Sen slopes for stream nitrate concentrations versus the Sen slopes for the potential drivers (i.e., streamflow, ammonium and nitrate concentration in atmospheric wet deposition) as well as stream ammonium versus potential drivers.

3. Results

From 1996 to 2007, mean stream nitrate concentrations at all EFR study catchments except Fernow were ≤0.16 mg NO₃–N l⁻¹; average nitrate at Fernow was 0.75 mg
Figure 2. Observed trends in monthly flow-weighted nitrate and ammonium concentration, streamflow, and nitrate and ammonium concentration in wet deposition for three time periods, calculated using Seasonal Mann–Kendall. Red denotes increasing trends, gray denotes no significant trends, and blue denotes decreasing trends for that period of time and catchment.

NO$_3$–N l$^{-1}$ (figure 1(b)). Ammonium concentrations in streams were equal to or below 0.01 mg NH$_4$–N l$^{-1}$ at 19 of the 21 study catchments; concentrations higher than 0.01 mg NH$_4$–N l$^{-1}$ were observed at Marcell (0.14 mg NH$_4$–N l$^{-1}$ at S2 and 0.05 mg NH$_4$–N l$^{-1}$ at S5). Most of the ammonium values were below detection at Fernow and Hubbard Brook (figure 1(d)). Catchments showed a wide range of mean annual streamflow, ranging from a low of 10.7 cm at Marcell-S5 to a high of 269.2 cm at Luquillo-Q3 (figure 1(c)). Mean annual wet deposition of dissolved inorganic N was highest at Fernow (5.6 kg ha$^{-1}$) and lowest at HJ Andrews (0.9 kg ha$^{-1}$; table S1 available at stacks.iop.org/ERL/8/014039/mmedia).

3.1. Trends over time in stream N concentrations

Stream nitrate concentrations, during the 1996–2007 period, significantly decreased in 11 of 22 reference catchments, increased in six, and showed no trend in five (figure 2). From 1987 to 2007, nitrate concentrations significantly decreased in seven of 17 catchments and significantly increased in four catchments. Over the 36 yr period between 1972 and 2007, the four Coweeta catchments showed significant increasing trends and the two catchments at Hubbard Brook showed decreasing trends (figure 2). The slopes of the observed significant trends ranged between $-0.7$ and $0.8$ µg NO$_3$–N l$^{-1}$ yr$^{-1}$ (figure S1 available at stacks.iop.org/ERL/8/014039/mmedia).

Within an EFR site, some reference catchments that were close to each other displayed opposite trends in stream N during the same time periods. For example, during the shortest time period evaluated (1996–2007), stream nitrate decreased at Coweeta-WS2 and Coweeta-WS18 but increased at Coweeta-WS27 and Coweeta-WS36 (figure 2). Similarly, during the 1983 and 1984–2007 period, stream ammonium decreased at HJ Andrews-WS8 and increased for HJ Andrews-Mack and HJ Andrews-WS2 (figures 3(g)–(j)).

Trends at some individual catchments were consistent over the entire period of collection (e.g., negative nitrate trends at HJ Andrews-WS9; figure 3(f)), whereas trends at other catchments changed direction depending upon the length of record analyzed. For example, HJ Andrews-Mack showed increasing stream ammonium concentrations when analyzing 25, 24, 23, 22 or 21 yr of record prior to 2007; no significant changes in stream ammonium when considering 20–13 yr of record; and decreasing stream ammonium concentration when analyzing 12 yr of record (figure 3(g)). In addition, the shift between positive and negative trends did not occur simultaneously among catchments or in nitrate and ammonium concentrations.

3.2. Associated trends and relationships between them

Streamflow showed significant decreasing trends at HJ Andrews, Fraser, and Coweeta-WS36 during the 1996–2007 period between 1972 and 2007, five of eight catchments (the four Coweeta catchments and HJ Andrews-WS9) showed significant increasing trends, and the two catchments at Hubbard Brook showed decreasing trends (figure 2). The slopes of the observed significant trends ranged between $-0.7$ and $0.8$ µg NH$_4$–N l$^{-1}$ yr$^{-1}$ (figure S1 available at stacks.iop.org/ERL/8/014039/mmedia).
Figure 3. Mean monthly flow-weighted (a) stream nitrate and (b) stream ammonium concentrations at HJ Andrews and trends in (c)–(f) nitrate and (g)–(j) ammonium concentrations at four HJ Andrews catchments. Trends are calculated for the recent 12 yr and then for longer periods by adding successive 1 yr increments. Red denotes increasing trends, gray denotes no significant trends, and blue denotes decreasing trends.

4. Discussion

Long-term data from reference forested catchments provide a unique opportunity to evaluate complex patterns of stream N concentrations over more than four decades across the USA. Through synthesis of data from 22 reference catchments at seven EFRs, we find that there are trends in stream N concentrations even at these minimally disturbed reference sites and that they present considerable spatial and temporal variability both among catchments within sites and among sites.

4.1. Spatial and temporal variability in trends

Nitrogen in human-altered streams and rivers of USA has been shown to increase during recent decades (Smith...
et al 1987, Richards and Baker 1993, Johnson et al 2009, Dubrovsky et al 2010). However, in the reference forested streams of the Northeast (Hubbard Brook), we found decreasing trends in stream nitrate, which supports the previous findings of Likens and Bormann (1995) and Campbell et al (2007) for Hubbard Brook and Goodale et al (2003) for the White Mountain region of New Hampshire. Stream nitrate also declined in the Pacific Northwest (HJ Andrews) and in Puerto Rico (Luquillo). Still, these trends are not consistent at national or at local scales, since Fraser in the Mountain West, and Fernow and half of the Coweeta catchments in the South, showed increasing trends in nitrate, suggesting that the controls on stream N concentrations vary spatially among sites.

Adding to these complex spatial patterns of trends, catchments within an EFR sometimes had opposing trends for the same N species for the same period of time. For example, we found opposing trends in stream nitrate concentrations among catchments within Coweeta from 1996 to 2007 and in stream ammonium at HJ Andrews from 1983/1984 to 2007. Over longer time scales, trends among catchments within sites tended to be more consistent, although fewer long-term records were available for these analyses. Additionally, stream nitrate and ammonium did not show consistent trends or coincident timing in trend shifts. Because catchments from the same site do not necessarily present the same direction in trends during the same time period, extrapolation of trends in space or across species of N should be made with extreme prudence.

The length of record is a major factor influencing detection of trends; trends for several catchments were not consistent over time. The inclusion of additional years in the time series analyzed shifted the direction or significance of trends in a number of catchments. This highlights that even when trends for short periods are statistically significant, they are not necessarily indicative of longer-term patterns. Therefore, there is need for caution in extrapolating trends over time. It is also important to recognize that statistically significant trends, even using the Seasonal Kendall test which is more robust than regressions for analysis of trends, might be ecologically insignificant. If the magnitude of change is extremely small, such as observed for stream nitrate at the HJ Andrews or stream ammonium at Hubbard Brook (figure S1 available at stacks.iop.org/ERL/8/014039/mmedia), the impacts of a significant trend on processes or functions may be minimal.

Our data are unique because they represent high frequency data of at least biweekly long-term sampling from reference sites. The detectability of trends depends on each site’s ability to precisely analyze solutes, but because of the improvement of analytical methods over the duration of these studies, detection limits may change over time. By recensoring monthly flow-weighted concentrations prior to the analysis and using the highest detection limit for the full period included in the analysis: we avoided trend artifacts. This meant that we were able to evaluate long-term trends that were not influenced by differing detection limits over time.

4.2. N concentrations and magnitude of trends

In general, stream N concentrations at the forested reference catchments included in this study were low in comparison to concentrations found in urban or agricultural streams and in the lower range of undisturbed catchments reported by other studies (Clark et al 2000, Binkley et al 2004). In contrast to what has been recently observed nationwide (Sprague et al 2009), stream nitrate concentrations in our forested reference sites showed a higher proportion of significant trends (77% this study, 33% Sprague et al 2009) and a higher tendency for decreasing trends in stream nitrate (50% this study, 27% Sprague et al 2009). The slopes of the trend observed in our reference streams (between −10 and 8.2 µg NO₃−N l⁻¹ yr⁻¹) were in the middle range of those observed by Sprague et al (2009) between 1993 and 2003 in streams with similar mean nitrate concentrations (between −31.7 and 40.0 µg NO₃−N l⁻¹ yr⁻¹). However, the relative magnitude of change in stream N concentrations should be considered when interpreting trends over time. For instance, during the 1996–2007 period, stream nitrate at Coweeta-WS2 and Coweeta-WS18 decreased by 0.3 µg NO₃−N l⁻¹ yr⁻¹ while increases of 1.6 and 0.8 µg NO₃−N l⁻¹ yr⁻¹ were observed at Coweeta-WS27 and WS36, respectively. This variability in the absolute magnitude of change is reduced when comparing the percentage of change of the mean (−4% yr⁻¹, −2% yr⁻¹, 4% yr⁻¹ and 3% yr⁻¹ at Coweeta-WS2, WS18, WS27 and WS36, respectively).

Ammonium concentrations in our study were less than nitrate concentrations, except at the peatland catchments of Marcell. Likewise, ammonium concentrations showed a smaller range of variation among catchments, results also observed by Clark et al (2000) and Binkley et al (2004). At some sites, ammonium values were close to the detection limit. This would help to explain the high variability in trends from year to year in the detailed analysis of HJ Andrews ammonium data, where small changes in N transformation pathways within a catchment might result in changes in trends. Additionally, data that are below the detection limit (which end up as ties in the ranking for the analysis of trends) coupled with occasional detectable concentrations might explain significant ammonium trends with a slope of 0 µg N l⁻¹ yr⁻¹ at Hubbard Brook or Fernow.

4.3. Possible drivers of changes in stream N

Trends in stream N concentrations were not synchronous with trends in potential drivers such streamflow or N concentrations in wet atmospheric deposition. Some of the correlations between trends were significant for one time period and not significant for others, indicating a possible temporal change in the variables driving those trends. Moreover, the lack of consistent correlations between trends in stream N concentrations and N in wet deposition reflects transformations that N species entering the catchment undergo both in the terrestrial and aquatic ecosystems.

Unlike trends observed in other broad-scale studies (e.g., Smith et al 1987 or Sprague et al 2009), trends in
stream N concentrations in our reference catchments should reflect changes in stream N concentrations that are not related to anthropogenic perturbations other than atmospheric deposition. The observed changes in stream N concentrations most likely reflected effects of change in climatic drivers, such as hydrology and temperature. Changes in streamflow (Lins and Slack 1999) and in the timing and magnitude of precipitation (Pielke and Downton 2000), could lead to changes in the relationship between N transport per unit of water volume (e.g., a relatively constant amount of N being transported by changing quantity of streamflow would lead to a changing trend in stream N concentration). Additionally, changing hydrology may affect N availability and transformation processes (Dahm et al 2003). Changes in air temperature, although not always paralleled to changes in stream-water temperature (Arismendi et al 2012), would affect microbial activity and N cycling rates within the catchment (Brookshire et al 2011). Moreover, stream N concentration is expected to change during forest succession, as a result of changing net ecosystem productivity as a forest ages (Vitousek and Reiners 1975, Vitousek 1977, Goodale et al 2003). Therefore, some of the observed trends could be caused by forest successional dynamics, including long-lasting legacy effects of past anthropogenic events (Bain et al 2012) or natural disturbances (Rhoodes et al 2013, supplementary material S1 available at stacks.iop.org/ ERL/8/014039/mmedia). Local catchment factors, including aspect, micrometeorology, vegetation, geology, soils, and natural disturbances can affect how N is transported and processed in catchments and ultimately, influences trends in N concentrations. These findings suggest that even in reference catchments, N concentrations in these streams are not necessarily stationary over time (Milly et al 2008).

5. Conclusions

Understanding whether nutrient concentrations are changing over time in reference streams is vital for good management and protection of water resources. The data presented here provide a unique opportunity to document changes in N concentrations in streams in the absence of changes in land use or other anthropogenic impacts except atmospheric deposition. Trends in stream N concentrations show high spatial variability both within and among sites, and our results demonstrate the transient nature of trends. The direction and significance of trends varied with record length at some catchments, a finding that reinforces the value of long data records, the need of properly pairing record lengths for catchment comparisons and the importance of caution when extrapolating trends from short time periods to longer periods.

Synthesis of long-term stream chemistry data from multiple catchments is valuable for understanding trends and for determining spatial variation across the USA, while showing some perils of broadly extrapolating information from individual catchment studies or short data records. Local factors including catchment characteristics and natural disturbance events influence trends within a site. Differences of trends within and among EFRs highlight a need for considering multiple reference catchments at both site and national levels to serve as benchmarks against which we can evaluate more heavily human-modified ecosystems. Reference catchments are also essential to improve our basic understanding of patterns and processes governing element cycles within intact ecosystems. Both of these functions can inform the management of N-pollution effects (e.g. through establishment of water quality standards or total maximum daily loads). These results also emphasize the importance of site-specific strategies that are relevant to choice of catchments and sampling schemes; such information is vital when considering trends, the refinement of existing programs, and establishment of new monitoring sites.

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