Nutrient fluxes in forests of the eastern Sierra Nevada mountains, United States of America

Dale W. Johnson and Richard B. Susfalk
Desert Research Institute and University of Nevada, Reno
Randy A. Dahlgren
Department of Land, Air and Water Resources, University of California, Davis

Abstract. Soil nutrient contents and fluxes in semiarid lodgepole (Pinus contorta [Dougl.]) and Jeffrey pine (P. jeffreyi [Grev. and Balf.]) stands of the eastern Sierra Nevada mountains are described and compared to those in the Integrated Forest Study sites [Johnson and Lindberg, 1992]. These Sierran forests, like others in the southwestern United States, have very low N, S, and H+ fluxes compared to more humid forests. Base cation fluxes in these Sierran forests are high relative to more humid forests, however, reflecting the high base status of the soils, inputs from nearby desert systems, and high rates of soil weathering. Soil C and N contents in these Sierran forests are low compared to those in more humid forests, probably because of lower primary productivity and more frequent fire. Soil extractable P pools in these Sierran forests vary by 2 orders of magnitude and are strongly influenced by parent material. As in most snow-dominated systems, pulses of NO3 are released from the melting snowpack each spring in the Sierran forests. Nitrogen released from melting snowpack is retained in the soil in most cases, but there are substantial springtime pulses of NO3 in stream waters during dry years. Budget calculations indicated that N losses during fire (both wildfire and prescribed fire) and N gains associated with postfire N-fixing vegetation are an order of magnitude greater than N inputs and outputs via solution phase.

1. Introduction

In comparison to more humid regions, there is a paucity of information about nutrient cycling in semiarid forests. There has been some nutrient cycling work on ponderosa pine (Pinus ponderosa Laws.) [e.g., Klemmedson, 1975; Hart and Firestone, 1989] and lodgepole pine (Pinus contorta Dougl.) ecosystems [Fahey, 1983; Fahey and Knight, 1986; Fahey and Yavitt, 1988; Schimel and Firestone, 1989], but these are relatively few in number compared to studies in more humid forests [e.g., Cole and Rapp, 1981; Johnson and Lindberg, 1992]. With the exception of Stark's [1973] study in Jeffrey pine (Pinus jeffreyi Grev. and Balf.), very little is known about the cycling of nutrients in forests of the eastern Sierra Nevada mountains.

Better knowledge of nutrient cycles in forests of the eastern Sierra Nevada will allow intelligent assessments of forest management practices and the effects of exogenous influences such as fire, air pollution, and climate change. Sierran forests, like those in much of the southwestern United States [Arno, 1996] have become increasingly susceptible to catastrophic wildfire because of fuel buildups due to past fire suppression. In addition, recent mortality due to drought and insect attacks have resulted in substantial increases in standing dead timber. Prescribed fire is actively being considered as an alternative to total fire suppression in these systems. Nitrogen losses during fire (either wild or prescribed) and N gains due to the invasion of N-fixing vegetation after fire have not been adequately quantified.

Sierran forests also play a major role in water quality of the region by retaining nutrients, especially N, which might otherwise enter the sensitive surface waters of the region. The deterioration of water quality in Lake Tahoe over the last few decades has been clearly documented and attributed to increased N inputs as a result of land development, atmospheric deposition, and N fixation by riparian vegetation [Goldman et al., 1993; Coats et al., 1976; Leonard et al., 1980; Byron and Goldman, 1989; Jassby et al., 1994].

The objectives of this study are to report progress to date on studies of nutrient cycling in forests of the eastern Sierra Nevada and to compare these results with those from a variety of forest ecosystems in more humid climates using the Integrated Forest Study database [Johnson and Lindberg, 1992].
2. Sites and Methods

The Little Valley site is located approximately 30 km southwest of Reno, Nevada in the eastern Sierra Nevada mountains. Elevation in the valley ranges from 2010 to 2380 m. Vegetation is dominated by Jeffrey pine (Pinus jeffreyi [Grev. and Balf.]) and lodgepole pine (Pinus contorta Dougl.) at lower elevations and white fir (Abies concolor [Gord. and Glend.] Lindl.) at higher elevations. Snowbush (Ceanothus velutinus Dougl.) occurs in dense patches throughout the valley and dominates the site of a recent (1981) wildfire just east of the valley. Mean annual temperature (MAT) near the valley floor is 5°C and mean annual precipitation (MAP) is 700 mm, approximately 50% of which falls as snow (H. Klieforth, personal communication, 1996). The study site is located on Marla soil series, a sandy, mixed Aquic Cryumbrept derived from colluvium of decomposed granite. Overstory vegetation consists of lodgepole pine with occasional Jeffrey pine. Understory vegetation consists of sage (Artemesia tridentata Nutt.) and various grasses and forbs.

The Sagehen Creek watershed is located approximately 10 km north of Truckee, California. Elevation ranges from 1830 to 2500 m. MAP and MAT at the Sagehen field station (elevation of 1830 m) are 870 mm and 4.8°C, respectively (H. Klieforth, personal communication, 1996). More than half of the total precipitation is in the form of snow. The study site is located on the Fugawee soil series, a fine-loamy, mixed frigid Ultic Haploxeralf derived from andesitic lahar and tuff. These soils meet all the chemical and mineralogical criteria for andic soil properties (Andisols); however, the bulk density is slightly in excess of the 0.9 g cm⁻³ requirement [Soil Survey Staff, 1994]. Overstory vegetation consists of 80 to 160-year-old Jeffrey pine and white fir. Understory consists primarily of occasional Ribes spp. and squaw fir (Ceanothus prostratus Benth.).

Over a 6 year period (1989 - 1995), snowmelt, soil solutions, and stream water have been collected from various sites at Little Valley and Sagehen Creek Watersheds. Some of these data has been reported previously [Johnson, 1995; Johnson et al., 1996]. Owing to a combination of fiscal and logistical limitations, it was not possible to collect solutions from all sites simultaneously. The most comprehensive data sets on nutrient fluxes were collected from the Little Valley site in the 1994-1995 and 1995-1996 seasons (October - September) and from the Sagehen site in the 1995-1996 season, and these data will be summarized here.

Snowmelt collectors and ceramic tension lysimeters (5 cm in diameter) were installed in six randomly located positions within a 0.10 ha plot at each site. Snowmelt collectors consisted of buried collection bottles to which the open 178 cm² collectors were attached. The open collectors consisted of cutoff tops of polypropylene bottles fitted with a drainage tube which was attached to the buried collection bottle. The open collectors were partially buried and open just above the soil surface. A glass wool plug was installed at the bottom of the upper collector to filter out debris. These devices collected rain or throughfall (depending upon their location) during the snow-free seasons and snowmelt during the snow season. The collection bottle was fitted with tubing which was run up poles so that collections of snowmelt solutions were possible from beneath the snowpack without disturbance. Ceramic cup lysimeters were installed at 15 and 30 cm depths in the mineral soil at Little Valley and at 30 cm at Sagehen. The lysimeters were fitted with an extra tube which extended to the bottom of the lysimeter, which, along with the vent tube, allowed removal of soil solutions and reestablishment of vacuum under snowpack without disturbance. Soil solutions were collected during snowmelt periods under a falling head tension set initially to 0.04 MPa. Further details on methodology of collecting snowmelt and soil solutions from beneath the snowpack are given by Johnson [1995] and Johnson et al. [1996]. All solutions were analyzed for electrical conductivity, pH, alkalinity (titration to pH 4.5), and cations (Ca²⁺, Mg²⁺, K⁺, Na⁺, and NH₄⁺) by Dionex ion chromatography, anions (Cl⁻, NO₃⁻, orthophosphate, and SO₄²⁻) were analyzed by Dionex ion chromatography, total N (Kjeldahl digestion followed by colorimetric analysis) and Si were analyzed by ICP spectroscopy.

Soil bulk density and percent gravel were estimated at all sampling depths at each site (n=4) by a modification of the quantitative pit method described by Hamburg [1984]. This modification involved removal of all soil from each randomly located pit (approximately 50 cm square), 1 cm screening in the field, and weighing of both fractions in a field moist condition. A subsample of the < 1 cm fraction was collected for moisture content and subjected to a further 2 mm screening in the laboratory. Bulk density of the soil fraction was determined by coring of the pit walls in the field, and bulk density of the coarse fraction was measured by displacement of subsamples in the laboratory. The total coarse fragment content (> 2 mm) and dry soil (< 2 mm fraction) was then calculated for the entire pit by horizon. With these values, soil and coarse fragments contents for the pit can be calculated without having to take the time to excavate a pit of known volume.

Soil samples for chemical analysis were taken by horizon from the bulk density pits plus two additional points taken by bucket auger at the Sagehen site and by pit at Little Valley (n=6). Soils were analyzed for total C and N with a Perkin-Elmer 2400 CHN Analyzer and for extractable P by 0.5 M HCl plus 1 M NH₄F followed by automated colorimetric analysis [Olsen and Sommers, 1982]. Exchangeable cations and cation exchange capacity were determined by extraction with 1 M NH₄Cl (exchangeable Ca²⁺, Mg²⁺, K⁺, Na⁺, and Al³⁺) followed by an ethanol wash to remove interstitial solution and then extraction with 1M KCl (cation exchange capacity) [Johnson et al., 1991]. Cation exchange capacity (CEC) is expressed as either the sum of cations, CECeness which is equal to sum exchangeable Ca²⁺, Mg²⁺, K⁺, Na⁺, and Al³⁺, or effective cation exchange capacity, CECeff which is equal to CEC determined by the final KCl extraction. Similarly, base saturation (BS) is defined as either percent BSess = [(exchangeable Ca²⁺, Mg²⁺, K⁺, Na⁺)/CECessen] x 100) or CECeff = [(exchangeable Ca²⁺, Mg²⁺, K⁺, and Na⁺)/CECeff] x 100).

We used the chloride balance method [Juang and Johnson, 1967; Lindberg and Johnson, 1989] to estimate solution nutrient fluxes. Chloride fluxes to the soil surface were measured directly from water volumes and concentrations in the snowmelt collectors beneath the forest canopy. We used these rather than the open collectors in order to better incorporate dry deposition of Cl⁻ into the calculations [Juang and Johnson, 1967]. It was then assumed that Cl⁻ fluxes through the soil were equal to inputs via snowmelt (i.e., that Cl⁻ was a conservative tracer), and soil water fluxes were calculated on this basis. These water fluxes were used in conjunction with soil solution concentrations to estimate soil leaching rates for the various ions.
3. Results and Discussion

3.1 Soils

The sandy-textured Marla soil at Little Valley had higher bulk density and substantially lower coarse fragments content than the andic Fugawee soil at Sagehen (Table 1). The two soils had similar C and N concentrations in the A horizons, but the Marla soil had lower C and N concentrations in subsurface horizons by an order of magnitude. C/N ratios were substantially higher in the A and BA horizons of the Marla soil, but the differences are not statistically significant (Student’s t test, p<0.05).

Base saturation by the sum of cations method (percent BSsum) in both soils was near 100% (Table 1), reflecting the semiarid nature of these forest ecosystems. Throughout the Marla soil profile and in the BC horizon of the Fugawee soil, effective cation exchange capacity (CECex) (as determined by NH₄Cl followed by KCl extraction) was uniformly less than cation exchange capacity by the sum of cations method (CECsum), and percent BSsum was uniformly greater than 100% (not shown). This situation can occur when some of the base cations (notably Ca²⁺ and Mg²⁺) extracted with NH₄Cl originate from precipitates (e.g., carbonates) rather than from exchange sites, and is also reflective of the semiarid nature of these ecosystems.

The greatest difference between the two soils was in NH₄F/HCl-extractable P, which was 2 orders of magnitude greater in the Marla than in the Fugawee soil (Table 1). Both the relatively high subsoil C and N concentrations and low available P concentrations in the Fugawee soil reflect the effects of parent materials derived from andesitic lahar and tuff (Waca series, a loamy-skeletal, mixed, frigid Andic Xerochrept). The moderately high C/N ratios in the LV and SH sites probably reflect a less advanced stage of soil organic matter decomposition, especially in the LV site (Anderson, 1992).

The extractable P content of the LV site was intermediate among the IFS sites, but that in the SH site is by far the lowest (Figure 2, top). The next lowest soil available P content among the IFS sites is in the red alder stand (Alnus rubra Bong.) (RA) at Thompson, Washington, where there is evidence of P immobilization (organic and inorganic) associated with excessive N fixation and soil acidification (Van Miegroet et al., 1992). Even in the red alder soil, however, extractable P levels (4 kg ha⁻¹) were over an order of magnitude greater than in the SH soil.

Soil base cation pools in the SH and LV soils were third and fourth highest, respectively, among the IFS sites (Figure 2, bottom). These high values were due to high base saturations in the LV and SH soils: in the A and E horizons, they were first and third highest, respectively, and in the B horizons they are the highest of all the IFS sites (Figure 3). Base saturations in the LV and SH sites were considerably greater than in the other cold and high-elevation IFS sites (NS, FL, MS, ST, SB, HF, TL, and WF).

Table 1. Concentrations of C, N, Extractable P, Cation Exchange Capacity, and Base Saturation in Soils From the Little Valley and Sagehen Sites

<table>
<thead>
<tr>
<th>Horizon (Depth, cm)</th>
<th>C, %</th>
<th>N, %</th>
<th>C/N</th>
<th>Extractable P, μg g⁻¹</th>
<th>CECex, a cmol kg⁻¹</th>
<th>CECex, b cmol kg⁻¹</th>
<th>BSsum, a %</th>
<th>BSsum, b %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Little Valley, Nevada</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (0-15)</td>
<td>3.37±1.28</td>
<td>0.11±0.09</td>
<td>32±13</td>
<td>10.0±3.2</td>
<td>8.76±3.79</td>
<td>6.72±3.03</td>
<td>95±4</td>
<td>130±26</td>
</tr>
<tr>
<td>BA (15-30)</td>
<td>0.58±0.17</td>
<td>0.01±0.007</td>
<td>60±24</td>
<td>7.8±2.9</td>
<td>3.95±0.46</td>
<td>2.73±0.60</td>
<td>96±2</td>
<td>143±29</td>
</tr>
<tr>
<td>BC (30-50)</td>
<td>0.26±0.05</td>
<td>0.01±0.007</td>
<td>30±15</td>
<td>5.6±2.3</td>
<td>3.44±0.55</td>
<td>2.11±0.40</td>
<td>97±9</td>
<td>164±45</td>
</tr>
<tr>
<td>C (50+)</td>
<td>0.20±0.04</td>
<td>0.01±0.007</td>
<td>25±11</td>
<td>3.6±2.3</td>
<td>3.59±0.74</td>
<td>2.34±0.15</td>
<td>98±2</td>
<td>149±22</td>
</tr>
<tr>
<td><strong>Sagehen, California</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (0-15)</td>
<td>3.83±1.28</td>
<td>0.15±0.04</td>
<td>25±3</td>
<td>0.22±0.25</td>
<td>18.24±6.61</td>
<td>18.58±3.14</td>
<td>93±10</td>
<td>92±29</td>
</tr>
<tr>
<td>BA (15-30)</td>
<td>3.17±0.80</td>
<td>0.13±0.03</td>
<td>24±4</td>
<td>0.04±0.04</td>
<td>14.37±2.02</td>
<td>17.31±1.88</td>
<td>96±3</td>
<td>80±14</td>
</tr>
<tr>
<td>BC (30-45)</td>
<td>2.09±0.48</td>
<td>0.10±0.01</td>
<td>21±4</td>
<td>0.04±0.04</td>
<td>15.47±2.21</td>
<td>16.89±6.31</td>
<td>97±3</td>
<td>112±76</td>
</tr>
</tbody>
</table>

CEC, cation exchange capacity; BS, base saturation. Standard deviations are given; n=6.

a Sum of cations method.
b Neutral salt (NH₄Cl) method.

and more similar to those in the warmer and low-elevation soils (CP, LP, DL, RA, and DF). This undoubtedly reflects the lower rates of leaching at the LV and SH sites.

### 3.2 Nutrient Fluxes

The fluxes of water, $H^+$, N, S, and base cations in both Sierran sites are shown in Table 2. Water flux estimates for the Little Valley site show very low evapotranspiration (ET) during the snowmelt season in 1994-1995 as compared to 1995-1996. This may be due to erroneous assumptions in the use of the Cl balance method. Chloride can serve as a tracer for input-output wa-

ter budget calculations if there is no mineral source of Cl [Juang and Johnson, 1967]; however, Cl is taken up and cycled by vegetation and can be released by fire [Turner and Kelly, 1973; Chorover et al., 1994]. Thus Cl cycling may have contributed to the low calculated ET values in Little Valley in 1994-1995. In 1995-1996, the Cl balance method gives an average ET value of 48 cm for Little Valley and 33 cm for Sagehen (comparing under-canopy inputs with estimated soil water flux), values which are comparable to the 33-72 cm reported by Leonard et al. [1980] for Ward Creek in the Tahoe Basin.

Fiscal limitations precluded intensive measurements of snowpack ion contents and dry deposition. Dry deposition to the snowpack in these studies would have been collected as snowmelt, and thus an upper estimate of net plus dry deposition to snowpack can be estimated from the under-canopy snowmelt fluxes. The values for under-canopy snowmelt fluxes of inorganic N ranged from a low of 49 mol, ha$^{-1}$ yr$^{-1}$ in Little Valley during the 1994-1995 season to a high of 259 mol, ha$^{-1}$ yr$^{-1}$ at Sagehen during the 1995-1996 season (Table 2). We believe this to be an upper estimate because it ignores both foliar leaching and leaching from litter incorporated into the snowpack.

Regardless of potential errors in soil water flux and dry deposition estimates, certain patterns in nutrient flux are quite clear. Ion budgets at both sites were characterized by low fluxes of $H^+$, N, and S, high fluxes of base cations, and high variability. Or-

Figure 2. (top) Soil extractable P and (bottom) sum of base cations (Ca+ Mg + K + Na) in the Integrated Forest Study sites [from Johnson and Lindberg, 1992] and the Little Valley, Nevada (LV), and Sagehen, California (SH), sites. See Figure 1 caption for abbreviations.
ganic N fluxes during the 1995-1996 season were generally lower than inorganic N fluxes (the exceptions being soil solutions at Little Valley and open snowmelt at Sagehen). (The data set on organic N was insufficient to calculate fluxes for Little Valley in the 1994-1995 season.) Base cations in solutions were balanced to a large degree by HCO₃⁻, with a consistent anion deficit in throughfall and soil solutions suggesting that organic anions were also present [Johnson et al., 1996]. At both sites, there was a substantial increase in the fluxes of ions in under-canopy snowmelt as compared to in the open and a substantial decrease from under-canopy snowmelt to soil solution. Inorganic N and P released from the under-canopy snowpack were almost totally immobilized within the soil (soil solution fluxes ranged from 1-15% of snowmelt fluxes under the canopy).

At both the Little Valley and Sagehen sites, there were pulses of NO₃⁻ from the snowpack during snowmelt which did not pass through the soil (Figure 4). In the Little Valley site, there was a very distinctive pulse late during the winter 1994-1995 and an earlier, less distinct pulse during the winter of 1995-1996. The differences in NO₃⁻ release from snowpack between these 2 years was probably due to the timing of the snowmelt: during 1994-1995, there was one late season melt, whereas during 1995-1996 there was both an early and a late season melt. In both years, soil solution NO₃⁻ concentrations were very low throughout snowmelt. At the Sagehen site, there was a late season NO₃⁻ peak in the winter of 1995-1996 which also did not pass through the soil (although soil solution NO₃⁻ concentrations were generally greater than at the Little Valley site). (No data for the 1994-1995 season are available for the Sagehen site.)

Nitrate released from snowpack did pass through the soils of a red fir (Abies magnifica A. murr.) site in the upper Sagehen basin in the drier winter of 1993-1994 [Johnson et al., 1996], and there was a distinctive peak in stream water NO₃⁻ in Sagehen

### Table 2. Fluxes of Water and Selected Ions in Open Snowmelt (Snowmelt-O), Snowmelt Beneath the Forest Canopy (Snowmelt-C), and Soil Solution (30 cm depth) in the Little Valley and Sagehen Sites

<table>
<thead>
<tr>
<th>Level</th>
<th>H₂O, cm</th>
<th>H⁺</th>
<th>NO₃⁻</th>
<th>NH₄⁺</th>
<th>DON⁻</th>
<th>SO₄²⁻</th>
<th>H₂PO₄</th>
<th>BC°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Little Valley, Nevada 1994-1995</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM-O</td>
<td>81</td>
<td>6</td>
<td>14</td>
<td>8</td>
<td>IS</td>
<td>34</td>
<td>2</td>
<td>811</td>
</tr>
<tr>
<td>SM-C</td>
<td>75±11</td>
<td>8±4</td>
<td>16±5</td>
<td>33±29</td>
<td>IS</td>
<td>40±6</td>
<td>4±3</td>
<td>1813±1242</td>
</tr>
<tr>
<td>SS</td>
<td>71</td>
<td>1±0.03</td>
<td>1±1</td>
<td>1±1</td>
<td>IS</td>
<td>44±6</td>
<td>1±1</td>
<td>2509±236</td>
</tr>
<tr>
<td><strong>Little Valley, Nevada 1995-1996</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM-O</td>
<td>40</td>
<td>24</td>
<td>7</td>
<td>12</td>
<td>0.1</td>
<td>17</td>
<td>&lt;1</td>
<td>142</td>
</tr>
<tr>
<td>SM-C</td>
<td>90±46</td>
<td>46±13</td>
<td>62±45</td>
<td>130±211</td>
<td>15±10</td>
<td>40±21</td>
<td>9±12</td>
<td>1899±515</td>
</tr>
<tr>
<td>SS</td>
<td>52</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>9±21</td>
<td>30±9</td>
<td>35±14</td>
<td>&lt;1</td>
<td>2046±284</td>
</tr>
<tr>
<td><strong>Sagehen, California 1995-1996</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM-O</td>
<td>90</td>
<td>29</td>
<td>5</td>
<td>15</td>
<td>38</td>
<td>39</td>
<td>88</td>
<td>3419</td>
</tr>
<tr>
<td>SM-C</td>
<td>72±11</td>
<td>37±11</td>
<td>13±16</td>
<td>243±254</td>
<td>7±9</td>
<td>35±19</td>
<td>13±18</td>
<td>1174±215</td>
</tr>
<tr>
<td>SS</td>
<td>39</td>
<td>6±0.1</td>
<td>17±25</td>
<td>26±25</td>
<td>7±4</td>
<td>70±33</td>
<td>1±7</td>
<td>1935±429</td>
</tr>
</tbody>
</table>

Ion units are in mol ha⁻¹ yr⁻¹. Standard deviations are shown where available. Standard deviations for soil solution fluxes represent those due to variation in concentration only.

* SM-O, snowmelt, open; SM-C, snowmelt under canopy; SS, soil solution, 30 cm depth.

b Dissolved organic nitrogen.

c Sum of base cations (Ca²⁺ + Mg²⁺ + K⁺ + Na⁺).

d IS, insufficient number of samples.
"nitrogen saturation" because of the temporal uncoupling of snowmelt N release and biological N demand. Even without snowmelt inputs of N, the temporal uncoupling of N mineralization and vegetation uptake may allow NO$_3^-$ to pulse through the system. Stark [1973] found that most decomposition takes place beneath snowpack in Little Valley, as was later also found to be the case in other snow-dominated systems [Taylor and Jones, 1990; Brooks et al., 1996]. Decomposition beneath snowpack creates the potential for a buildup of mineralized nutrients which could be flushed down to the rooting zone during snowmelt.

Stark [1973] also showed that there is a spatial uncoupling of the N cycle in forests of Little Valley: because of dry summer conditions, roots are often entirely absent in the litter layers and upper soil horizons. Thus the competition between heterotrophs and plant roots that characterizes more mesic systems is absent in the Little Valley ecosystems. The same is likely true of the Sagehen sites, where similar lack of rooting in litter and upper A horizons has been noted.

Although the pulses of NO$_3^-$ in the Little Valley and Sagehen sites are of concern for water quality in the region, it is clear that fluxes of N, S, and H$^+$ in both sites are extremely low compared to the more humid IPS sites, including the relatively unpolluted systems in Washington state (Findley Lake (FL), Douglas-fir (DF), and Red Alder (RA); (Figures 6 and 7). Nitrogen deposition fluxes at the SH and LV sites were within the same order of magnitude as estimates for other montane/alpine sites in the western United States, including the nearby Tahoe Basin (70-340 mol N ha$^{-1}$ yr$^{-1}$) [Fahey and Yavitt, 1988; Lewis and Grant, 1980; Stohlgren et al., 1991; Stottlemeyer and Troendle, 1992; Williams et al., 1995, 1996; Jassby et al., 1994].

In contrast to N, S, and H$^+$, base cation inputs and leaching at the LV and SH sites were intermediate to high compared to the IPS sites (Figure 7, bottom). The high base cation inputs no doubt reflect high inputs of dust to these sites from nearby desert systems, and the high outputs reflect the relatively high base saturation of the soils, high weathering rates of primary minerals, and high rates of HCO$_3^-$ leaching in these systems.

3.3 Potential Effects of Fires and Postfire N fixation on N Balances

Both the LV and SH ecosystems are part of a landscape which has historically been strongly affected by fire. The frequency and intensity of wildfires in this region as well as throughout the
United States has increased over the last 2 decades [Arno, 1996]. Fire suppression efforts since European settlement may have delayed wildfires, but they cannot prevent them. Prior to 1900, low-intensity burns characterized ponderosa and Jeffrey pine sites which had average fire return intervals of 2.5-15 and 14-18 years, respectively [Dietrich, 1980; McBride and Jacobs, 1980]. After the early 1900s, fire suppression led to the establishment of numerous new trees in these ecosystems. The dense stands of young trees, lacking recurrent fires, readily build up high levels of fuels such that present-day fires are often catastrophic, killing virtually all the trees in the fire zone. There was just such a catastrophic fire near the Little Valley site in 1981 (Little Valley fire); there were 2 near the Sagehen site (the Dormer Ridge fire in 1961 and the Crystal Peak fire in 1994).

Some rough calculations of the effects of fire and N fixation with respect to postfire vegetation demonstrate that these have historically been the dominant factors regulating the N balances at these sites. On the basis of the data of Stark [1973] and biomass estimates for Jeffrey and lodgepole pine forests at the LV site, we conservatively estimate that the nearby Little Valley fire caused the direct loss of at least 300 and possibly as much as 800 kg N ha⁻¹ (i.e., assuming the loss of foliage and forest floor N pools but no change in soil N pools). The fire occurred when the forest was approximately 100 years old, and thus the annualized loss would be 3 to 8 kg N ha⁻¹ yr⁻¹ or 1 to 2 orders of magnitude greater than N losses by leaching. Nitrogen fixation rates of snowbush (Ceanothus velutinus), the shrub which now dominates the Little Valley, range from 70-100 kg N ha⁻¹ yr⁻¹ in a series of studies in the Oregon Cascades [Youngberg and Wollum, 1976; Binkley et al., 1982; McNabb and Cromack, 1983]. Fixation rates may be less in the drier climates of the LV and SH sites but are almost certainly greater than the 1-3 kg N ha⁻¹ yr⁻¹ inputs in snowmelt (beneath canopy). Previous studies at five paired sites in the northern part of Little Valley showed that soils beneath snowbush contained an average of approximately 1000 kg N ha⁻¹, more N (mostly in labile form) than soils beneath adjacent pine stands [Johnson, 1995; D.W. Johnson, unpublished data, 1996].

In response to the threat of catastrophic wildfires, prescribed understory fire has been reintroduced to these systems as a means of keeping fuel loads down. Stark [1973] conducted a prescribed fire in Little Valley and measured a net loss of 264 kg N ha⁻¹ from the forest floor. With the typical burn interval of 10 years, this N loss rate would also clearly exceed that due to leaching.

Thus, in a longer-term perspective, fire and postfire N fixation have been and probably will continue to be the most important
factors affecting N balances in these eastern Sierran sites. More research on fire and its effects on both C and N budgets in these systems is underway.

4. Conclusions

The Little Valley and Sagehen sites, like most montane sites in the western United States, have low N and S inputs compared to more humid regions of the eastern United States and Europe. There are exceptions to this generalization, however; the ponderosa pine sites studied by Fenn et al. [1996] in the San Bernardino mountains of southern California have levels of N deposition (>30 kg N ha⁻¹ yr⁻¹) commonly associated with highly polluted regions and are apparently near N saturation. Thus data on N fluxes in the relatively unpolluted Little Valley and Sagehen sites provide a valuable baseline against which the effects of increasing pollutant inputs can be measured as population growth continues at a very rapid pace in this region.

The intermittent NO₃⁻ pulses in stream waters at Little Valley and Sagehen suggest that these sites might be at stage 0 or even pre-stage 0 in Stoddard's [1994] proposed format for evaluation of N saturation. However, it is important to note that NO₃⁻ released from the melting snowpack did not pass through the soil profile or appear in stream waters during the course of this particular study. Only during drier years do we have any evidence that these systems allow the passage of NO₃⁻ from melting snow through the soil and into stream waters.

Even a cursory analysis shows that fire (both wildfire and prescribed fire) and N fixation by postfire Ceanothus at these sites are the dominant mechanisms by which N is removed from and added to these ecosystems. Even from the perspective of water quality, fire, along with parent material effects on N and P in soils, may play a dominant role. Postfire erosional inputs of soils derived from decomposed granite will obviously have a much greater impact on the transport of labile P to surface waters than inputs from andic soils, whereas the reverse is true for N. Thus, while it is important to continue to monitor N fluxes via solution phase because of water quality issues and as a baseline against future increases, further emphasis on the effects of fire on the nutrient fluxes in these ecosystems is required to fully understand the major mechanisms regulating N dynamics in these semiarid ecosystems.

Acknowledgments. Research was supported by the Nevada Agricultural Experiment Station, University of Nevada, Reno. Field help by Hal Klieforth and laboratory technical help by Valerie Yurieaga and Zengshou Yu are greatly appreciated.

References


— R.A. Dahlgren, Department of Land, Water and Air Resources, University of California, Davis, Davis, CA 95616. (e-mail: radahlgren@ucdavis.edu)

D.W. Johnson and R.B. Susfalk, Desert Research Institute and University of Nevada, Reno, Reno, Nevada 89506. (e-mail: dwj@maxey.dri.edu)

(Received November 1, 1996; revised June 2, 1997; accepted June 11, 1997.)