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Throughfall studies of deposition to forest edges and gaps in montane ecosystems

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Abstract. An extensive network of bottle/funnel collectors was used to measure hydrologic, SO_4^{2-}, and NO_3^- fluxes in rain events and in throughfall beneath the canopies of several high elevation forest stands in the Great Smoky Mountains National Park during 1989—1990. The throughfall fluxes were used as deposition surrogates to quantify trends in atmospheric inputs to sapling trees growing in forest gaps and to the mature forest canopy at the edge surrounding each gap. The paired gap/edge stands were located above (1940 m) and below (1720 m) the base of the clouds typically impacting this mountain. Total hydrologic and ion fluxes beneath the edge trees during the forest growing season exceeded fluxes beneath the adjacent gap saplings by nearly a factor of three (e.g. 230 vs 88 meq m^{-2} for SO_4^{2-}) at both elevations. Water and SO_4^{2-} fluxes were up to two times greater beneath the forest edge at the cloud-prone 1940 m site than at 1720 m (e.g. 230 vs 110 meq m^{-2} for SO_4^{2-}). However, throughfall NO_3^- fluxes were about 30% higher at 1720 m (17 vs 13 meq m^{-2}), because this lower site receives greater dry deposition of HNO_3 due to its ridgetop location and greater wind penetration. Estimates of SO_4^{2-} deposition from cloud impaction were consistent with the net throughfall flux of SO_4^{2-} (throughfall flux minus rain flux) at the 1940 m forest edge, but greatly exceeded the net throughfall flux at 1940 m gap, suggesting differences in ion concentrations in cloud droplets impacting on mature edge trees and young saplings in forest gaps.

Introduction

The health of forest ecosystems in mountainous terrain is an indicator of environmental stress (Johnson & Siccama 1983). High elevation forests are exposed to natural stresses, and they are also subject to high rates of atmospheric deposition and elevated levels of some air pollutants (Lovett & Kinsman 1990). The combination of high ion concentrations in cloud

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water, high wind speeds, and frequent cloud immersion results in deposition rates much higher than in comparable low elevation forests (Lovett & Kinsman 1990). For this reason, studies have concentrated on the responses of such forests to air pollutants and on the role of atmospheric deposition in their biogeochemical cycles (McLaughlin et al. 1990; Friedland et al. 1984; Johnson et al. 1991). A complicating factor in understanding the influence of atmospheric deposition on these forests in their heterogeneity, characterized by extremes in canopy density and topography. The frequency of canopy gaps and edges in such areas may be quite high as a result of climatic or insect disturbances. This is important since the distribution of canopy cover exerts a significant influence on air/surface exchange. Deposition at forest edges often exceeds that in the interior of a stand due to structural effects on turbulent exchange (Wiman & Agren 1985).

Deposition trends from edge effects are impossible to quantify in complex terrain by conventional micrometeorological methods (Hicks et al. 1986). However, the collection of forest throughfall has proved useful for defining trends in water and ion fluxes across a variety of terrain and canopy features (Hasselrot & Grennfelt 1987; Draaijers et al. 1988; Lindberg et al. 1990; Joslin & Wolfe 1992; Weathers et al. 1992). Hydrologic fluxes in throughfall in montane ecosystems are often used as indicators of cloudwater interception (e.g. Lovett 1984). Throughfall also yields a direct estimate of sulfur deposition in forests, since foliar leaching of SO_4^{2-} is small (Garten et al. 1988), and deposited sulfur is quantitatively washed from the canopy by precipitation (Lindberg & Garten 1988).

Here we report on the results of a two-year study of throughfall fluxes of water, sulfate, and nitrate in three spruce stands in the southern Appalachian Mountains. The study quantified trends in deposition in natural gap and edge features at two elevations in the spruce/fir zone. This research was an extension of the Integrated Forest Study (IFS) of atmospheric deposition and its role in biogeochemical cycling in 13 diverse forests (Johnson & Lindberg 1992). Observations at the IFS deposition site in the Smoky Mountains over several years indicated that cloud base was typically at or above ~1800 m. Because of the influence of cloud exposure on deposition in mountain forests (Lovett et al. 1982), we established new sites located in natural gaps in the mature spruce canopy located above (1940 m) and below (1720 m) the original IFS site to determine fluxes over a range of conditions. The work reported here is part of ongoing studies designed to test throughfall as a measure of atmospheric fluxes in highly complex terrain (e.g. Lindberg et al. 1988; Lindberg et al. 1992; Weathers et al. 1992; Nodvin et al. 1992).

Sites and methods

During the IFS, several plots were established in spruce forests near Noland Divide (35°34′N, 83°28′W) on Clingman's Dome in the Great Smoky Mountains National Park, North Carolina. One site at 1740-m elevation (the IFS site) was instrumented from 1985—1989 with automated precipitation collectors and a 33-m meteorological tower containing climatologic and atmospheric chemistry sensors for intensive deposition and ion flux measurements (Johnson & Lindberg 1992). To determine relative trends in deposition for this study as influenced by elevation, canopy structure, and canopy height, we established throughfall plots at two additional sites: a lower elevation site, 350 m to the SE of the tower at 1720-m elevation, and a higher elevation site, 1.8 km to the W of the tower at 1940-m elevation and ~200 m below the summit of Clingman's Dome. All sites were sampled during the 1989 and 1990 growing seasons (defined as the non-snow period between April and October). The sites were situated on slopes of 15—20° with different aspects: 1940-m site, east; IFS site, southwest; and 1720-m site, near ridgetop, generally west.

The area near our plots is characterized by red spruce stands (*Picea rubens* Sarg.) of 200—300 y age. The primary understory consists of patches of regenerating Fraser fir [(*Abies fraseri*) (Pursh) Poir.] and red spruce. The overstory is dense but patchy, and the stands are interspersed with gaps where fir has been killed by a fungus transmitted by the balsam wooly adelgid. The height of the dominant spruce canopy ranges from 23 to 32 m, while saplings in the gaps range from 3 to 5 m. Mean annual precipitation (1986—89) at the tower site is 215 cm. These forests are described in Johnson & Lindberg (1992), Johnson et al. (1991), and McLaughlin et al. (1990).

During 1989, throughfall was collected below mature spruce trees at each of the tree sites, and also below saplings in canopy gaps at the 1720-m and 1940-m sites. Because of the remoteness of the sites, automatic, wet-only collectors were not feasible. Our collectors consisted of 1-l polyethylene bottles with polyethylene funnels of 7.5-cm diameter held 0.5—2 m above the forest floor on permanent posts. Six throughfall collectors were placed beneath randomly selected trees at each site (i.e. six replicate 'gap' and six replicate 'edge' samplers at the 1720-m and 1940-m sites). The 'edge' samplers were located in the edge of the mature forest surrounding each gap (see Fig. 1). At the IFS site, six replicate throughfall collectors were located in the interior of a mature stand ~30 m from the nearest edge (there were no gap samplers at this location). At each of the three sites, two replicate samplers were situated in a clearing unaffected by the forest canopy to collect incident precipitation. During 1990, the

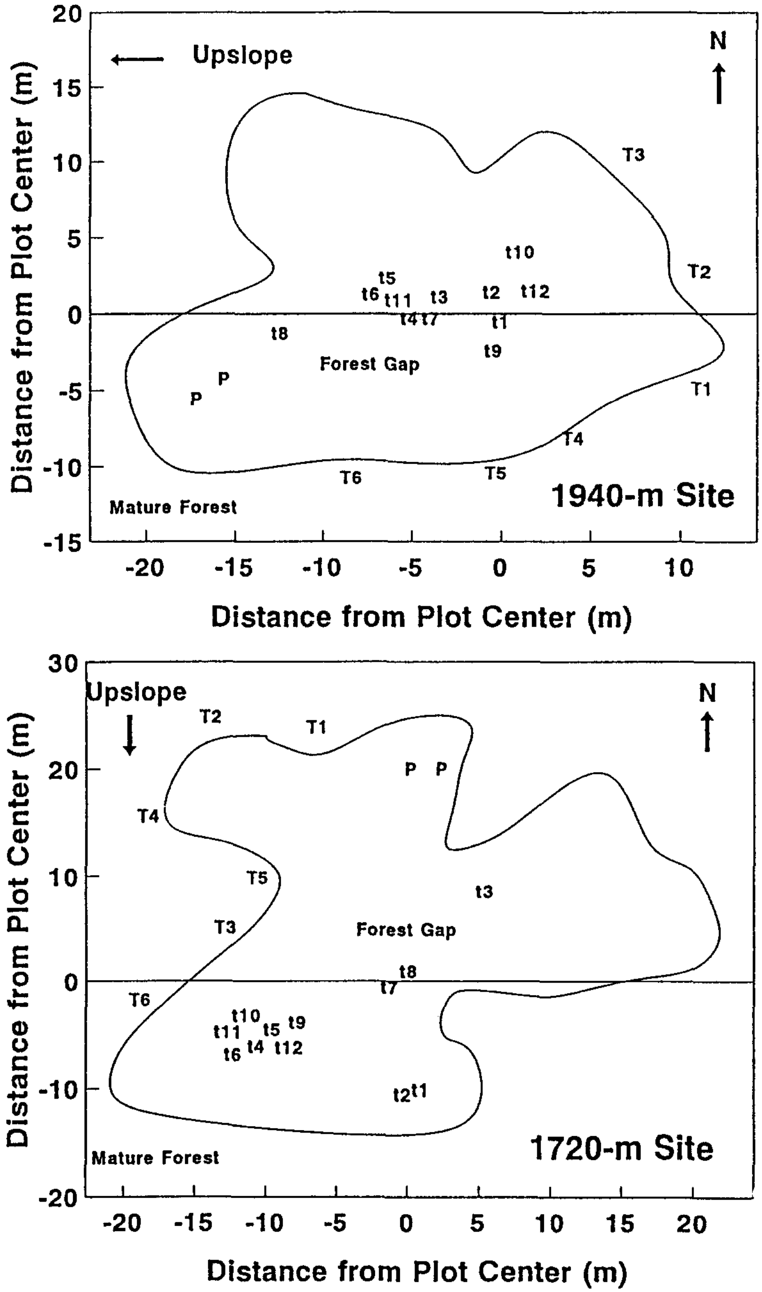

Fig. 1. Locations of throughfall collectors in forest gaps and surrounding edges in two forest plots at different elevations on Clingman's Dome in the Great Smoky Mt. National Park. Sampler codes are as follows: T1 = throughfall sampler number 1 below the edge of the mature canopy, t1 = throughfall sampler number 1 below the sapling canopy in a forest gap, P = sampler for incident precipitation in a forest clearing.

number of replicate throughfall collectors in each gap was doubled to better characterize spatial variability (i.e. with addition of collectors t7–t12 in Fig. 1) and the 'edge' collectors were discontinued.

Samplers were collected within 1–2 days after each rainfall event, but were not protected from dry deposition before events (the average exposure to dry deposition was 2–3 days). Similar collectors were shown to yield accurate estimates of wet-only fluxes of sulfate in throughfall, but to overestimate ion fluxes in wet-only precipitation collected in clearings (Richter & Lindberg 1988). Stemflow was found to be insignificant at the IFS site (~1–2% of the annual water and sulfate fluxes, Johnson & Lindberg 1992) and was not measured in this study. Hydrologic fluxes were determined from measurements of sample volume plus plastic wedge-type rain gages adjacent to each sampler (for a total of 12–24 replicates per site). The event samples were preserved upon collection with chloroform (10 μl/30 ml sample), and were volume-composited in the laboratory by location (e.g. gap at 1940 m, edge at 1720 m, etc.) over ~2-week intervals. On several occasions, the replicate throughfall samples were analyzed separately for a measure of the within-plot variability in fluxes. Sample pH was measured on return to the laboratory, and all samples were stored at 4 °C for analysis of sulfate and nitrate by ion chromatography within 4 weeks of collection (Johnson et al. 1991).

Results and discussion

Elevation trends in measured fluxes

The sites at each elevation received similar rainfall during the 1989 growing season (within ± 8%), but substantial differences were found in the throughfall fluxes (Table 1). Hydrologic fluxes in throughfall were ~50% higher at 1940 m than at 1720 m for gap and edge trees, and these trends were very consistent throughout the 1989 growing season (Fig. 2). Throughfall regularly exceeded precipitation in both the forest edge and gap at the 1940-m site, but not at 1720 m. Fluxes of water in throughfall that are in excess of rainfall indicate the presence of measurable cloud interception (i.e. net throughfall > 0, where net throughfall = throughfall – precipitation) (Lovett et al. 1982). The temporal trends in *net* throughfall fluxes at these sites (Fig. 3) suggest that the trees at the 1940-m site were influenced by cloud interception during nearly all of the 1989 sampling periods, and that cloud input in the gap was closely related to that at the surrounding forest edge ($r = 0.60$, $P < 0.05$, $N = 12$ events).

Clouds apparently occurred much less frequently (or with a much

Table 1. Total seasonal hydrologic and ion fluxes to several different forest plots located at stand edges, centers of stands, and in forest gaps at two elevations on Clingman's Dome, Great Smoky Mt. National Park. The total throughfall fluxes are the means (±1 SE) of six spatially replicated collectors in each plot.

Site	Elevation (m)	Period*	Hydrologic (cm) and ion fluxes (meq m^{-2})					
			Indicent precipitation			Throughfall		
		1989	H_2O	SO_4^{2-}	NO_3^-	H_2O	SO_4^{2-}	NO_3^-
Forest edge, mature spruce	1940	4/18—10/31	143	60	17	185(4)	230(12)	13(2)
Forest gap, sapling spruce	1940	4/18—10/31				155(15)	88(15)	8.9(1.4)
Forest interior, mature spruce (IFS site)	1740	4/18—10/31	149	45	15	110(6)	93(10)	11(2)
Forest edge, mature spruce	1720	4/18—10/31	137	47	15	132(11)	110(11)	17(2)
Forest gap, sapling spruce	1720	4/18—10/31				100(11)	66(6)	10(1)
		1990						
Forest gap, sapling spruce	1940	5/7—10/17	99	54	15	91(10)	70(8)	12(2)
Forest gap, sapling spruce	1720	5/7—10/17	101	45	14	78(9)	59(10)	10(3)

* For the 1989 period (196) days: $n = 12$ samples from 23 events at the 1940- and 1720-m sites, and $n = 23$ events at the 1740-m site.
For the 1990 period (163) days: $n = 12$ samples from 25 events at the 1940- and 1720-m sites, and $n = 25$ events at the 1740-m site.

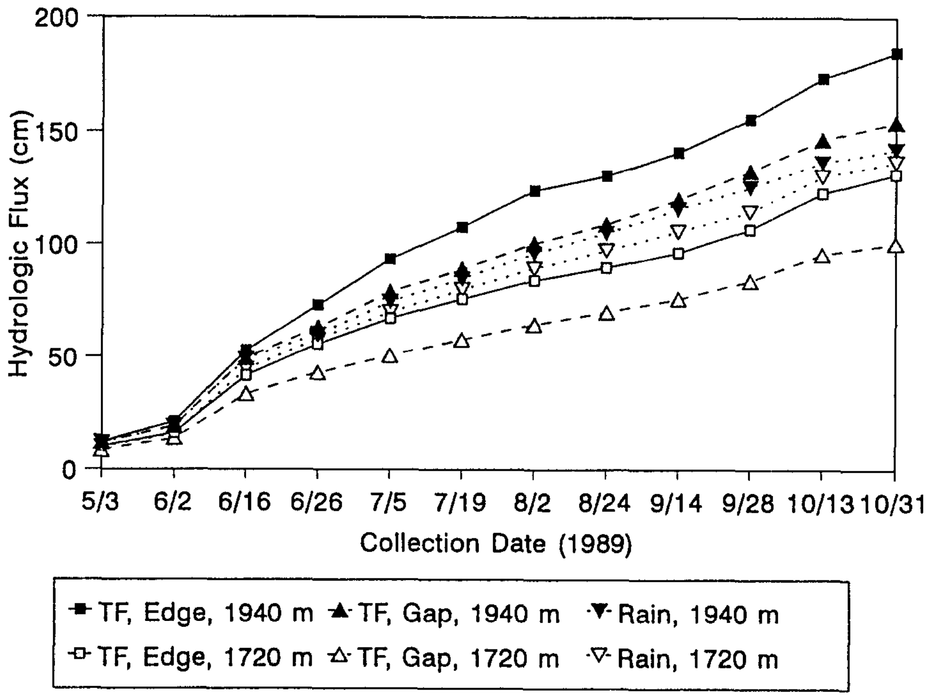

Fig. 2. Cumulative hydrologic fluxes in throughfall and rain during the 1989 growing season at each edge/gap site. Uncertainties for the seasonal throughfall fluxes are shown in Table 1. For individual events, the relative standard errors of the mean fluxes from the six replicate collectors were in the following ranges: 1—5% for edge trees and 9—15% for gap trees at 1940 m; 3—13% for edge trees and 10—22% for gap trees at 1720 m.

lower liquid water content) at the 1720-m site (Fig. 3; the correlation coefficient between *net* throughfall at the 1940-m edge site and that at the 1720-m edge site was 0.32). There was measurable cloud interception at the lower site only during those periods that experienced the largest cloud input at the 1940-m site (e.g. 6/16—7/5 and 9/28—10/31, Fig. 3). These elevational trends confirm visual observations made during the IFS — when clouds were present during the growing season, the cloud base generally remained above the 1740-m site (Petty & Lindberg 1990).

The expected influence of cloudwater on deposition is apparent from the ion fluxes in throughfall at these sites (Table 1). These trends are clearly related to differences in cloudwater exposure (and/or dry deposition washoff) since fluxes in incident precipitation were generally comparable (Table 1). Nitrate and SO_4^{2-} fluxes in rain were moderately higher at the 1940-m site than at the lower elevation sites, probably reflecting the more frequent mixed rain/cloud events at the 1940-m site (ion concentrations are commonly enriched in cloudwater relative to rain at these sites, and

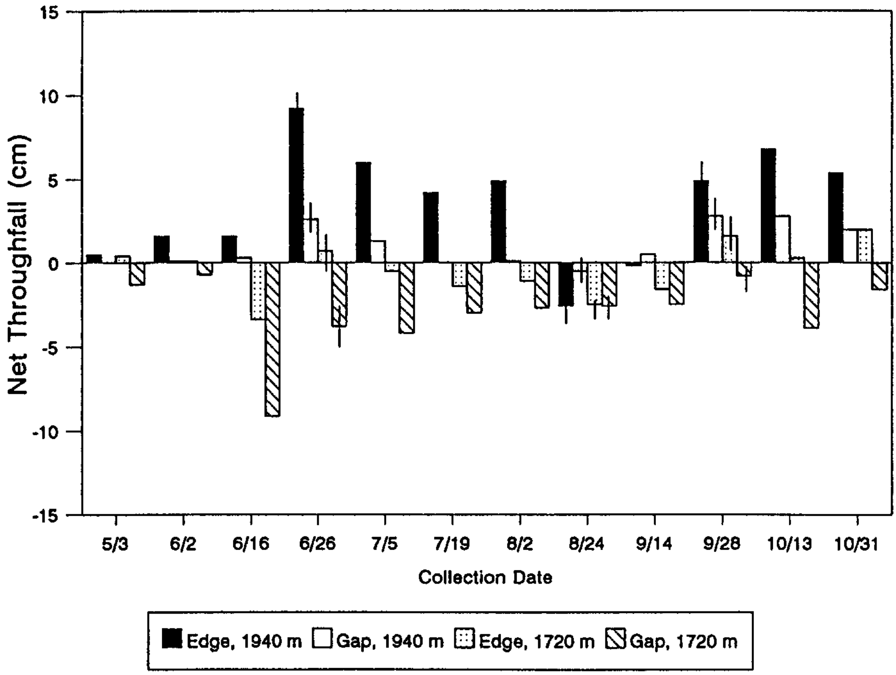

Fig. 3. Hydrologic fluxes in net throughfall events (net throughfall = flux in throughfall − flux in rain) during the 1989 growing season at each edge/gap site. Error bars (± 1 SE) are shown for three events.

some cloud droplets are captured by open funnel collectors; Lindberg et al. 1988). The trends in throughfall were different for the two ions and were much more pronounced for SO_4^{2-} than for NO_3^-. Total sulfate fluxes decreased with decreasing elevation, by a factor of 2 below the edge trees but by only ~20—30% beneath the trees in the gaps (for both 1989 and 1990). These trends were quite consistent throughout the 1989 growing season (Fig. 4). The elevational trends for NO_3^- during 1989 were the reverse of those for SO_4^{2-}. The total fluxes were higher at the 1720-m site than at 1940 m, by 30% at the edge sites. However, these trends were less consistent over time than those of SO_4^{2-} (Fig. 5), and there was no real trend in the flux of NO_3^- below the gap trees for either year.

Throughfall fluxes are highly variable within forest plots (e.g. Kostelnik et al. 1989), and interpretation of differences between sites is subject to considerable uncertainty. Variability is a function of several factors, and it is expected to increase with elevation because of the terrain, climatic, and canopy cover effects discussed earlier. We determined the statistical significance of the elevational trends based on the six replicate samplers

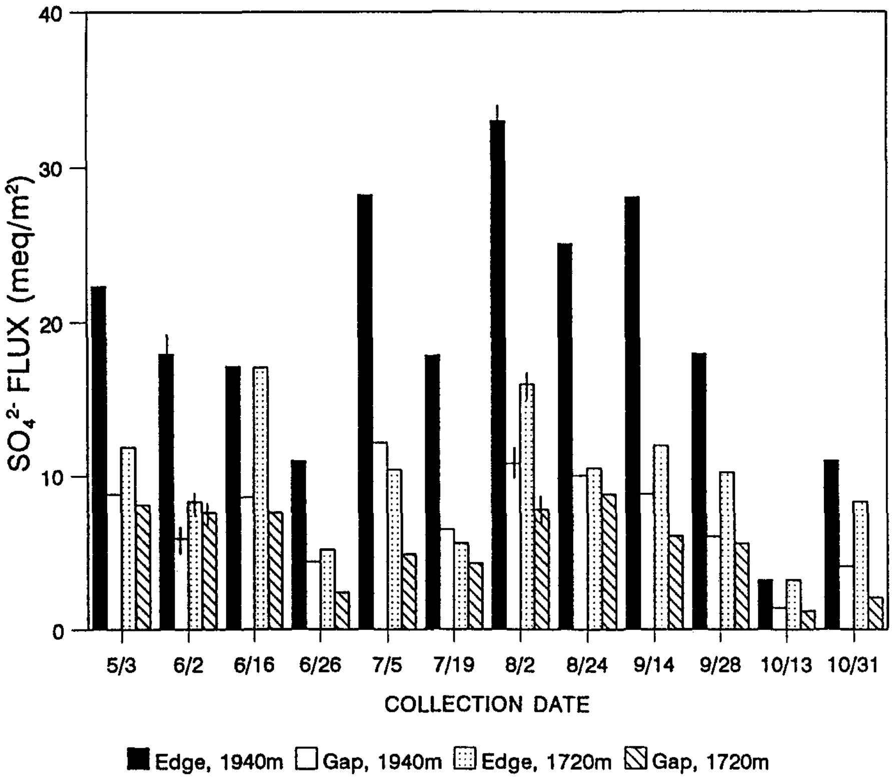

Fig. 4. Fluxes of sulfate in throughfall during the 1989 growing season at each edge/gap site. Uncertainties in the total seasonal fluxes are given in Table 1; individual error bars (± 1 SE) are shown for two events.

for those events which were not spatially-composited prior to analysis (Table 2). The flux of SO_4^{2-} in throughfall below the forest edge was significantly higher at 1940- than at 1720-m, but tree-to-tree variability was sufficient to reduce the significance of elevational trends in other ion fluxes. The hydrologic fluxes in throughfall were also significantly ($p <$ 0.01) higher below the edge and gap trees at 1940 m than below their counterparts at 1720 m.

Compared to the IFS data, the hydrologic fluxes measured at all sites during the 1989 growing season were ~40—50% higher than the mean fluxes for the 1986—1988 growing seasons (Table 3), while those during 1990 were more comparable to the earlier 3-y means. The wet deposition rates of SO_4^{2-} and NO_3^- at the lower elevation sites during the 1989 growing season were within ~10% of the mean fluxes at the nearby IFS site during the 1986—1988 growing seasons (Table 3), despite the much

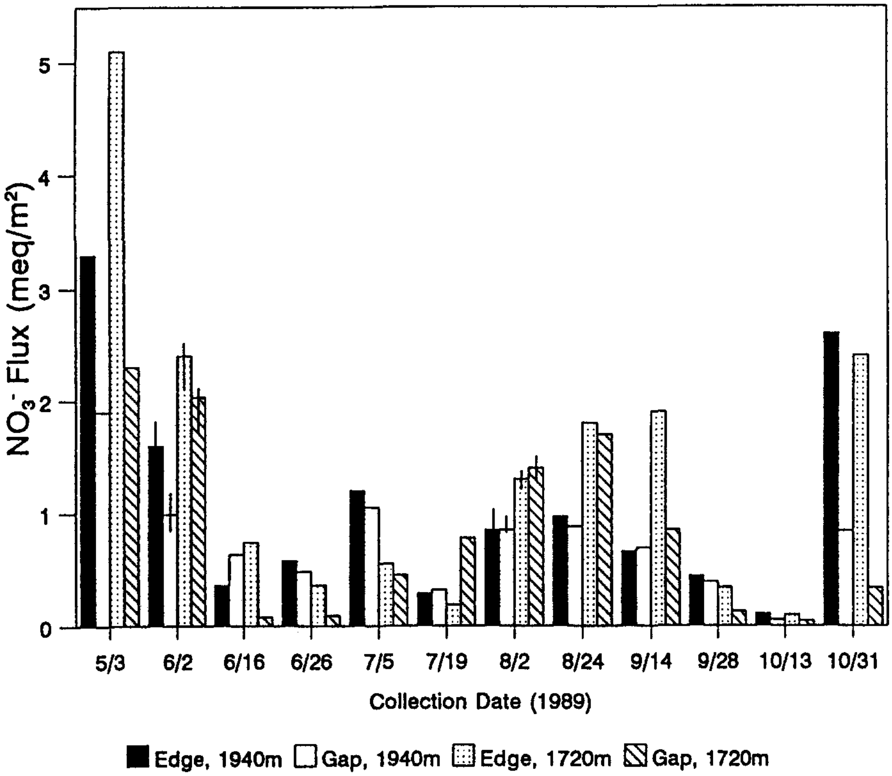

Fig. 5. Fluxes of nitrate in throughfall during the 1989 growing season at each edge/gap site. Uncertainties in the total seasonal fluxes are given in Table 1; individual error bars (±1 SE) are shown for two events.

Table 2. Results of *t*-tests for unpaired plots to determine significance of differences in ion fluxes between edge and gap plots and between 1940- and 1720-m elevation sites. The data included the 12 events collected during 1989 which were analyzed separately for each of the six replicate collectors at each plot (these samples represent ~70% of the total rainfall during this period). Shown are the values of *t* and the levels of significance (using Student's *t*-test for unpaired plots). The values in the upper right portion of the table are for sulfate fluxes, while those in the lower left portion are for nitrate.

	1940 m, Edge	1940 m, Gap	1720 m, Edge	1720 m, Gap
1940 m, Edge		8.2**	7.3**	NA
1940 m, Gap	1.8		NA	0.9
1720 m, Edge	1.7	NA		3.3**
1720 m, Gap	NA	1.3	2.8*	

SULFATE

NITRATE

* = $p < 0.05$, ** = $p < 0.01$

Table 3. Mean hydrologic and ion fluxes to the 1740-m IFS site for 1986—1989 (for details see Lindberg & Lovett 1992; Johnson & Lindberg 1992).

	Annual means*			Growing season means**		
	H_2O (cm)	SO_4^{2-} (meq m^{-2} y^{-1})	NO_3^-	H_2O (cm)	SO_4^{2-} (meq m^{-2})	NO_3^-
Vapors		26	62		17	43
Fine particles		13	0.30		12	0.19
Coarse particles		16	13	14	8.8	
Total dry deposition		55	75		43	52
Precipitation	203	60	23	100	41	15
Fog/cloud input	41	110	26	6	18	3.2
Total deposition	244	220	120	106	100	70
Throughfall flux	214	240	87	91	140	41
Stemflow flux	2	5	0.2	0.6	3	0.1
Total throughfall and stemflow	216	250	87	92	140	41
Net throughfall		190			100	

* For April 1, 1986—March 31, 1989
** The average growing season for the IFS site was taken as April 1—October 31 during each year.

higher rainfall during 1989. This indicates that the concentrations in rain during the wetter 1989 period were diluted roughly in proportion to total rainfall, suggesting that wet deposition to sites on Clingman's Dome may be limited by atmospheric concentrations and not by rainfall. This phenomenon has been reported for mountain sites in Sweden (Granat 1988). The similarity in the wet deposition fluxes to the 1720-m site during the wetter 1989 and dryer 1990 growing seasons also supports this idea (Table 1). Despite the comparable ion fluxes in wet deposition, the SO_4^{2-} and NO_3^- fluxes in throughfall at the IFS site were ~40—70% lower during 1989 than during the 3-y IFS sampling period (cf. Tables 1 and 3). This suggests somewhat lower inputs by cloudwater and dry deposition at the IFS site during the 1989 growing season.

Edge and gap effects on throughfall

At both elevations, location of the throughfall samplers below trees in canopy gaps or below trees at the edge of the surrounding forest had a strong influence on the measured fluxes (Table 1). Enhanced interception of cloudwater by the mature trees at the forest edge increased the hydrologic fluxes in the throughfall by ~20—30% relative to gap trees at both elevations (rainfal input to edge and gap trees was assumed to be the same), and this effect was relatively consistent over time (Fig. 2). The hydrologic flux below the forest interior at the 1740-m IFS site was ~15% lower than that below the forest edge at the nearby 1720-m site. Similar differences in hydrologic fluxes in throughfall below forest edge and forest interior trees have been reported for a spruce stand influenced by cloud impaction in the Catskill Mountains (Weathers et al. 1992), but we are not aware of published data on similar trends between forest gaps and their surrounding edges.

The enhanced cloud interception by mature trees resulted in much larger edge effects on ion fluxes in throughfall than seen for water (Table 1). The flux of SO_4^{2-} below the forest edge at 1940 m was nearly 3 times higher than below the nearby gap, and at 1720 m the flux below the forest edge was ~2 times higher than below the gap. For NO_3^- the fluxes were also higher at the forest edges than in the gaps, but the edge/gap ratio was somewhat higher at the 1720-m site, (1.7 compared to 1.5 at 1940 m). The edge effects on throughfall fluxes were very consistent over time for SO_4^{2-} but less so for NO_3^- (Figs. 4 and 5). Statistical analyses of the uncomposited samples from each plot revealed that the edge effects were significant for water, SO_4^{2-}, and NO_3^- at 1940 m, but only for NO_3^- at 1720 m (Table 2).

At the IFS forest interior site at 1740 m, the SO_4^{2-} flux below the canopy was ~15% less than that below the forest edge at the nearby 1720-m site, while for NO_3^-, the flux to the forest interior was ~50% lower than at the edge site. Similar differences in throughfall fluxes of SO_4^{2-} and NO_3^- at forest edge and interior sites have been reported at low elevation forests in Europe (Draaijers et al. 1988; Hasselrot & Grennfelt 1978; Lindberg et al. 1990), and at a high elevation forest in Virginia (Joslin & Wolfe 1991), but such data have not been published for canopy gaps and surrounding edges. Throughfall fluxes of these ions exhibit strong edge effects because of aerodynamic factors that enhance both cloudwater interception and dry deposition at forest edges. Clearly, forest gaps and associated edges exert a strong influence on landscape fluxes, and caution must be used in interpreting field measurements which do not take these factors into account.

Estimates of cloudwater interception and dry deposition from throughfall

Hydrologic fluxes

The flux of water in net throughfall (e.g. Fig. 3) is an underestimate of cloud inputs because of canopy interception and evaporation losses. We developed an approach with the 3-y data from the IFS site to correct for these losses. Using throughfall events from cloud-free periods (generally during the summer, but including non-snow winter data as well), we regressed interception loss (IL, calculated from net throughfall whenever throughfall $<$ rainfall) on event rainfall amount in an attempt to predict interception during cloud events: IL $= -0.07^*$ ppt -0.22 (SE's of regression coefficients = 0.02 and 0.34 respectively; $r = 0.62$, $n = 112$ events). The regression can be used to estimate an upper bound on interception loss during cloud periods, since we expect evaporation during in-cloud periods to be less than that associated with rain events (Lindberg & Johnson 1989). If the relationship for the IFS site applies to the forest edge sites as well, we can estimate a maximum cloud-water interception during the 1989 growing season: ~ 50 cm at the forest edge at 1940 m, ~ 5 cm at the edge at 1720 m, and no significant cloud-water interception at the forest interior site at 1740 m (Table 4). We did not have sufficient non-cloud event data for the sapling trees growing in the gaps to develop a similar regression. However, a rough estimate for gaps may be derived using the above approach, indicating cloud interception of ~ 20 cm in the 1940-m forest gap (~ 40% of that at the surrounding edge) and none at the 1720-m gap. Similar calculations suggest only 3 cm cloudwater input at the 1940-m gap site during the 1990 growing season, a period which experienced ~ 40% less rainfall than during the 1989 growing season.

During the IFS we measured the rate of cloud drip below mature trees for several rain-free periods (Schaefer et al. 1989; Lindberg & Johnson 1989). The mean drip rates varied widely (0.11—1.5 mm h^{-1}, mean = 0.62, SE = 0.22), but we can use these data to estimate a range in the duration of clouds at the 1940- and 1720-m sites. Such estimates would represent maxima since we expect drip rates at the edge to exceed those in the interior of the forest (by a factor of ~ 2 for sites in the Catskills; Weathers et al. 1992). Assuming a similar edge/interior ratio for the Smokies sites (i.e. a mean drip rate of ~ 1.2 mm h^{-1} for edge (trees), yields estimates of cloud exposure for the 1989 growing season derived from the mean ($\pm$ 1 SE) of: ~ 300—700 h at 1940 m, and ~ 30—100 h at 1720 m. These values suggest in-cloud frequencies of ~ 6—15% and ~ 0.6—2% at the 1940- and 1720-m sites, respectively. The 1986—1989 IFS data indicated annual cloud exposures of ~ 700—1000 h y^{-1} at 1740 m, primarily during November—March (Lindberg & Johnson 1989). These frequencies are generally lower than at other mountain sites in the eastern U.S. (~ 20—40%, Lovett & Kinsman 1990).

Table 4. Seasonal hydrologic and ion fluxes to forest edge and gap plots measured in net throughfall (NTF)*, and estimates of cloudwater hydrologic fluxes and ion fluxes to each plot based on analysis of throughfall fluxes during the 1989 growing season (see text).

Site	Elevation (m)	Hydrologic (cm) and ion fluxes (meq m^{-2})				
		Net throughfall		Estimated cloud fluxes and immersion**		
		H_2O (cm)	SO_4^{2-}	H_2O (cm)	Immersion (hr, %)	SO_4^{2-}
Forest edge, mature spruce	1940	42	170	50	300—700 (60—15%)	125
Forest gap, sapling spruce	1940	12	28	20	—	50
Forest interior, mature spruce	1740	−39	48	0	0	0
Forest edge, mature spruce	1720	−5	63	5	30—100 (0.6—2%)	12
Forest gap, sapling spruce	1720	−37	19	0	0	0

* NTF = Flux in throughfall − flux in incident precipitation.

** Immersion times are shown as a range determined from ± SE of the estimated mean.

Sulfate deposition

Ion fluxes by cloud interception are often predicted from the product of the evaporation-corrected net throughfall flux of water below a forest stand, and ion concentrations in cloud water collected nearby (e.g. Lovett et al. 1982; Joslin & Wolfe 1992; Weathers et al. 1992). We collected and analyzed cloudwater from the tower at the IFS site during the growing seasons of 1986—1989, and found a volume weighted mean SO_4^{2-} concentration of ~250 μeq/l for the 25 events sampled (Johnson & Lindberg 1992). Using this concentration and our estimates of hydrologic fluxes of cloudwater (Table 4), we estimate the following cloud interception fluxes for the 1989 growing season: 125 meq/m^2 to the edge at 1940 m, 50 meq/m^2 to the adjacent gap, and 12 meq/m^2 to the edge at 1720 m. Although crude, these estimates appear reasonable. For example, the SO_4^{2-} flux to the 1720-m edge site is somewhat lower than, but comparable to, the 3-y mean growing season cloud flux at the nearby 1740-m IFS site (Table 3), and at sites near 1000-m elevation at Shenandoah, VA and Mt. Moosilauke, NH (~15—20 meq/m^2). Inputs to the 1940-m sites are comparable to those for other higher elevation, near-summit sites (1500—2000 m) such as Whiteface Mt., NY, Whitetop Mt., VA, and Mt. Mitchell, NC (~60—160 meq/m^2, Mohnen 1988).

The measured fluxes of SO_4^{2-} in net throughfall at each site provide important checks on the calculated cloudwater fluxes. Net throughfall provides an estimate of the sum of cloudwater and dry deposition inputs to the forest canopy (e.g. Lindberg & Garten 1988; Lindberg & Lovett 1992). At the two edge sites, net throughfall exceeds our cloud estimates as expected because of dry deposition (Table 4). By difference (NTF-calculated cloud flux), the estimated dry deposition of SO_4^{2-} is on the order of 45 to 50 meq/m^2 at each site. Considering the uncertainties involved, these values are remarkably close to the 3-y mean dry deposition flux of SO_4^{2-} at the IFS site during the growing season (43 meq/m^2, Table 3), providing support for this method of estimating seasonal mean cloud inputs for these edge sites.

Our estimate of the SO_4^{2-} flux from cloud input compares much less favorably with the measured SO_4^{2-} flux in net throughfall at the 1940-m gap site; the estimated cloud flux exceeds that measured in net throughfall by nearly a factor of two (Table 4). If we use the net throughfall hydrologic flux uncorrected for interception loss (Table 4), the estimated cloud flux of SO_4^{2-} to the gap approaches the measured net throughfall flux of SO_4^{2-} (30 vs 28 meq/m^2), but it is unreasonable to assume no interception loss in the canopy. If our estimates of cloud hydrologic fluxes are reasonably accurate, this suggests that the cloud droplets that are collected by foliage in the gap site have a much lower average SO_4^{2-} concentration than does the cloudwater (collected from towers above the forest) that impacts on the mature trees at the forest edge. Ion concentrations in cloudwater typically decrease with increasing droplet diameter, due to dilution effects (Lovett 1981). Hence, larger droplets may be responsible for more of the water input to the gaps than to the exposed canopy surrounding them. Turbulent transport of droplets into the forest canopy results in interception by canopy surfaces of a wide range of droplet diameters, with efficiencies determined by surface characteristics, drop diameter, and wind speed. The wind flow in and around these forest gaps may create aerodynamic effects that result in capture of a higher proportion of larger wind-blown, and sometimes sedimenting, cloud droplets by the sapling trees than by mature trees at the forest edge. This suggests that water and SO_4^{2-} fluxes below canopy gap trees may not follow the same trends seen for mature trees.

This observation has important implications for cloudwater modeling and interpretation of throughfall fluxes at mountain sites, where this approach has been widely used to estimate cloud inputs (e.g. Lovett et al. 1982; Joslin & Wolfe 1992). Because this approach assumes a direct linear relationship between water and ion fluxes, the results could be subject to considerable error in some applications. Our data also suggest that relationships between the throughfall fluxes of water and SO_4^{2-} are site specific, or, in some cases nonexistent. Figure 6 illustrates the deviations of the fluxes of water and SO_4^{2-} below individual edge trees from the mean for the entire plot during each of five events. Several trees exhibited SO_4^{2-} fluxes that were consistent with those for water (e.g. number 3 at 1940 m and numbers 4 and 5 at 1720 m). However, some of the trees with relatively uniform trends in water fluxes exhibited highly variable trends in SO_4^{2-} (e.g. number 5 at 1940 m), or trends opposing those of water (number 1 at 1940 m and number 6 at 1720 m). All samplers were located beneath canopy dominant trees of roughly the same height at the forest edge, and we found no obvious tree characteristics to explain this behaviour (e.g. leaf area, branching shape, crown dominance). This level of complexity suggests that direct measurement of SO_4^{2-} fluxes in throughfall may provide the most accurate estimates of spatial trends in total SO_4^{2-} deposition in highly complex terrain.

Nitrate deposition

It is more difficult to intepret the trends in the NO_3^- fluxes in throughfall because of adsorption and biological uptake in the canopy (Garten & Hanson 1990), leading to lower NO_3^- fluxes in throughfall than in total deposition. However, there is a strong relationship between deposition and throughfall fluxes of NO_3^-, suggesting that useful information can be

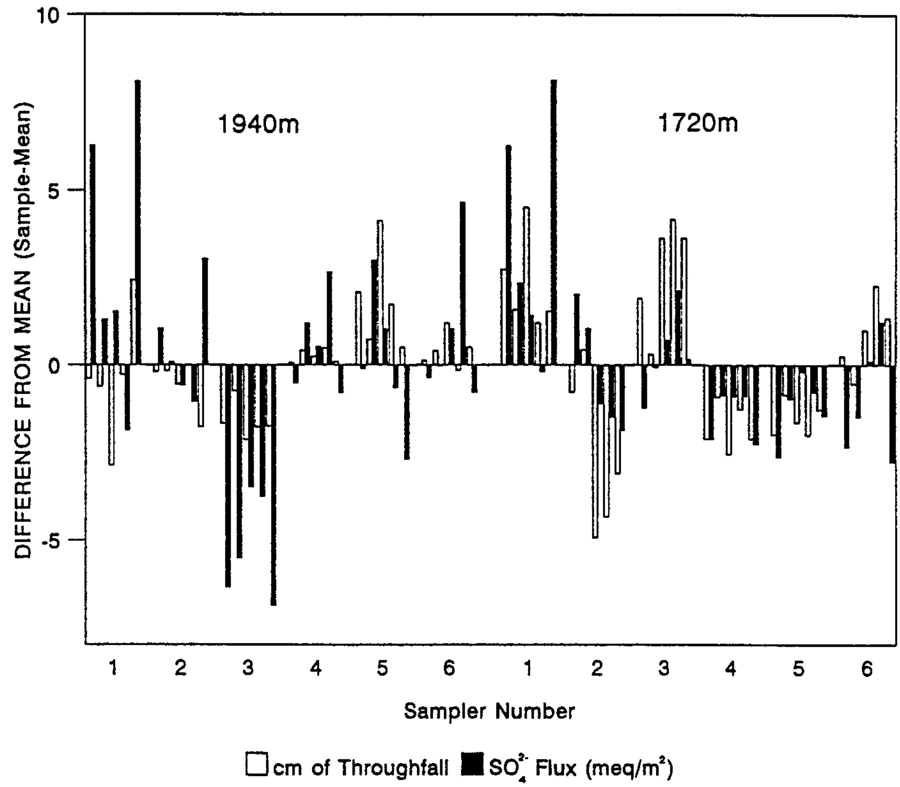

Fig. 6. Trends in hydrologic and sulfate fluxes beneath individual trees in the edge plots during 1989. The bars represent the difference between the flux for an individual sampler and the mean of the whole plot for five separate events (where the plot mean is calculated for all six samplers during each event).

found in throughfall fluxes (Lovett & Lindberg in press). Relative to SO_4^{2-}, NO_3^- fluxes in throughfall may be more strongly influenced by dry deposition than by cloudwater (Lovett & Lindberg in press). At the IFS site, NO_3^- input was dominated by dry deposition (75% vs 5% for cloud during the growing season), while cloudwater was the single most important source of SO_4^{2-} deposition, contributing twice as much as dry deposition annually (Table 3).

We expect similar differences between NO_3^- deposition by cloudwater and by dry deposition at the nearby 1720-m site, suggesting that dry deposition may explain the elevational trends in the throughfall NO_3^- fluxes. Since dry deposition of NO_3^- is controlled by HNO_3 vapor in these forests (Lovett & Lindberg in press) and atmospheric concentrations of HNO_3 should be similar at each elevation (e.g. Lovett & Kinsman 1991), the differences between sites are more likely due to the structure, aspect, and exposure of each stand. The 1940-m stand has an easterly aspect and is ~200 m below a steep ridge sheltering the site from the prevailing westerly winds. The 1720-m site is near ridgetop, resulting in greater wind penetration into the canopy. Dry deposition of HNO_3 is strongly controlled by wind speed and atmospheric turbulence (Huebert & Robert 1985), suggesting that higher dry deposition of NO_3^- would be expected at the 1720-m site. These conditions would also enhance cloud interception, but this effect is diminished by the infrequent cloud immersion at 1720 m (Table 4). Higher NO_3^- deposition at the 1720-m site is confirmed by the data of Van Miegroet et al. (1990) who found consistently higher levels of NO_3^- in high-tension soil water there compared to the 1940-m site.

Summary and implications

Our data reveal important differences in throughfall fluxes below gaps and edges of two forest stands at different elevations in the Great Smoky Mountains National Park. To the extent that atmospheric deposition of SO_4^{2-} is reflected in throughfall fluxes (e.g. Lindberg & Garten 1988), these trends indicate quantifiable differences in deposition to each site related to cloudwater and dry deposition. The edge/gap ratios in SO_4^{2-} fluxes at the cloud-prone 1940-m site (Table 5), represent a greater 'edge effect' over a distance of 10 m than has been reported between forest edge and interior sites over distances of 200 m for low elevation forests (Draaijers et al. 1988), and distances of 30 m for the other high elevation forests (Weathers et al. 1992). The location of the 1720-m site generally below cloud base, but on an exposed ridgetop, favors dry deposition over cloud input. These differences in site exposure are consistent with higher dry deposition of NO_3^- as HNO_3 at this site.

Our data also indicate that water and ion fluxes in throughfall may be related on some scales, but not on others. The hydrologic fluxes in throughfall beneath mature trees appear to be more strongly influenced by elevational effects, while ion fluxes are more strongly influenced by differences in canopy cover (edge trees vs those in canopy gaps). In addition, relationships between water and SO_4^{2-} fluxes beneath individual trees can be highly variable. Deposition of pollutants and nutrients by cloud impaction to mountain forests is often computed from canopy water balances based on throughfall hydrologic fluxes, using ion concentrations measured in cloud water collected nearby (e.g. Lovett 1988). Our estimates of cloudwater fluxes with this method were consistent with measured fluxes of SO_4^{2-} in net throughfall beneath the mature edge trees at both eleva-

Table 5. Sulfate fluxes in throughfall events during the 1989 sampling period, and ratios of fluxes between sites.

	SO_4^{2-} Flux (meq m^{-2})					Flux ratios			
	1940 m		1720 m			Edge/gap		1940 m/1720 m	
Date	Edge	Gap	Edge	Gap		1940 m	1720 m	Edge	Gap
5/3/89	22	8.8	12	8.1		2.5	1.5	1.9	1.1
6/2	18	5.9	8.3	7.6		3.1	1.1	2.2	0.8
6/16	17	8.6	17	7.6		2.0	2.3	1.0	1.1
6/26	11	4.4	5.2	2.4		2.5	2.2	2.1	1.8
7/5	28	12	10	4.9		2.3	2.1	2.7	2.5
7/19	18	6.5	5.6	4.3		2.8	1.3	3.2	1.5
8/2	33	11	16	7.8		3.1	2.1	2.1	1.4
8/24	25	10	11	8.8		2.5	1.2	2.4	1.1
9/14	28	8.8	12	6.1		3.2	2.0	2.3	1.4
9/28	18	6.1	10	5.6		3.0	1.8	1.8	1.1
10/13	3.2	1.4	3.2	1.2		2.3	2.7	1.0	1.2
10/31/89	11	4.1	8.3	2.1		2.7	4.0	1.3	2.0
					mean:	2.7	2.0	2.0	1.4
					Std Dev:	0.35	0.75	0.63	0.46
					CV:	13%	37%	32%	32%

tions. However, similar estimates for the 1940-m gap site were much higher than measured net throughfall fluxes. We suspect that aerodynamic effects associated with forest gap structure may result in an upward shift in the size spectrum of cloudwater droplets that actually impact on the sapling trees in these gaps. Since cloudwater concentrations are inversely related to droplet diameter, such shifts would reduce the average ion concentrations of cloudwater collected in the gaps. Further studies are needed to better understand the processes which influence cloud interception in and around forest gaps.

Edges and gaps are common to high elevation forest canopies (e.g. Sprugel & Bormann 1981), and their location relative to the cloud base exerts a strong influence on the deposition of airborne substances. The spatial trends we found in SO_4^{2-} fluxes to these sites were surprisingly stable over several months (Table 5). For 12 event samples, the edge/gap flux ratio at the cloud-prone 1940-m site exhibited a coefficient of variation (CV) of only 13%, suggesting that the influence of these canopy features may be relatively consistent under different conditions. Methods are needed to quantify and model atmospheric deposition in montane ecosystems because of their sensitivity to the impacts of both air pollution and climate stress, but highly complex terrain prevents the application of many standard methods to these regions. Our data suggest that measurement of SO_4^{2-} fluxes in throughfall is an effective tool to characterize these trends, and may be the only way to quantify SO_4^{2-} fluxes directly in some environments. This method could be used to determine the general patterns of deposition in high elevation forests for development of large-scale estimates of landscape fluxes (e.g. Weathers et al. 1992).

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