Ammonia volatilization from native grasslands and forests of southwestern Montana
by Asa Lovisa Aradottir

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biology
Montana State University

Abstract:

Ammonia volatilization from unfertilized and fertilized plots on two native grassland Sites and two native forest sites in southwest Montana was measured with a closed system. Volatilization rates from unfertilized plots ranged from 2.5 to 25 µgN m^-2 day^-1. Volatilization rates from fertilized plots averaged over the first week after fertilization (50 kgNH+4 -N ha^-1) were up to 2500 µgN m^-2 day^-1. Both may have been underestimates of actual volatilization because (1) efficiency of the closed system as measured in the laboratory was only 50-70% for corresponding ammonia concentrations and (2) alteration of the microenvironment within the absorption chambers may have resulted in lower NH3 -N volatilization rates within than outside of the chambers.

Ammonia volatilization from unfertilized plots in grasslands was highest in spring, nonsignificant to medium high during the summer, and was low but significant during the winter. In the two forest sites, significant losses were measured only in spring and summer. Rates of volatilization from fertilized plots where the process was not limited by availability of ammoniacal N showed that conditions were more favorable for the volatilization process in summer than winter; volatilization rates were high in summer and low in winter at all sites. Low volatilization from unfertilized plots in grassland sites in the summer was attributed tp low availability of ammoniacal N.

A crude estimate of annual NH3-N volatilization gave 19, 26, 2,5, and 8 gN ha^-1 yr^-1 for sites in Stipa comata/Bouteloua gracilis, Agropyron spicatum/Bouteloua gracilis, Pseudotsuga menziesii/Carex geyeri, and Abies lasiocarpa/Vaccinium scoparium habitat types respectively. Declines in temperature and pH and increases in water availability, organic matter, and cation exchange capacity as one moves up an altitudinal gradient from the Stipa comata/Bouteloua gracilis habitat type to the Abies lasiocarpa/Vaccinium scoparium hgbitat type were correlated with NH3 -N volatilization rates and might explain corresponding declines in volatilization. Such declines were especially marked in loss from fertilized plots.

AMMONIA VOLATILIZATION FROM NATIVE GRASSLANDS AND FORESTS OF SOUTHWESTERN MONTANA

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Ammonia volatilization from unfertilized and fertilized plots on two native grassland sites and two native forest sites in southwest Montana was measured with a closed system. Volatilization rates from unfertilized plots ranged from 2.5 to 25 μgN m^{-2} day^{-1}. Volatilization rates from fertilized plots averaged over the first week after fertilization (50 kgNH_4^+-N ha^{-1}) were up to 2500 μgN m^{-2} day^{-1}. Both may have been underestimates of actual volatilization because (1) efficiency of the closed system as measured in the laboratory was only 50-70% for corresponding ammonia concentrations and (2) alteration of the microenvironment within the absorption chambers may have resulted in lower NH_3-N volatilization rates within than outside of the chambers.

Ammonia volatilization from unfertilized plots in grasslands was highest in spring, nonsignificant to medium high during the summer, and was low but significant during the winter. In the two forest sites, significant losses were measured only in spring and summer. Rates of volatilization from fertilized plots where the process was not limited by availability of ammoniacal N showed that conditions were more favorable for the volatilization process in summer than winter; volatilization rates were high in summer and low in winter at all sites. Low volatilization from unfertilized plots in grassland sites in the summer was attributed to low availability of ammoniacal N.

A crude estimate of annual NH_3-N volatilization gave 19, 26, 2.5, and 8 gN ha^{-1} yr^{-1} for sites in *Stipa comata/Bouteloua gracilis, Agropyron spicatum/Bouteloua gracilis, Pseudotsuga menziesii/Carex geyeri*, and *Abies lasiocarpa/Vaccinium scoparium* habitat types respectively. Declines in temperature and pH and increases in water availability, organic matter, and cation exchange capacity as one moves up an altitudinal gradient from the *Stipa comata/Bouteloua gracilis* habitat type to the *Abies lasiocarpa/Vaccinium scoparium* habitat type were correlated with NH_3-N volatilization rates and might explain corresponding declines in volatilization. Such declines were especially marked in loss from fertilized plots.

CHAPTER 1

INTRODUCTION

The amount of nitrogen in an ecosystem depends on the initial concentration, additions to the ecosystem and losses. Additions include biological fixation of atmospheric N_2, inputs due to animal transfer, and deposition of atmospheric nitrogen oxides and ammonia. Losses include export by animals, leaching, runoff, denitrification, and volatilization of nitrogen oxides and NH_3. System inputs, system losses and the nitrogen cycle have all received scientific attention (e.g., Soderlund and Svensson 1976, Clark and Rosswall 1981). The study of gaseous losses of NH_3 from plant soil systems has, however, been limited to tilled systems (Terman 1979) and pasture systems (Floate 1981, Simpson and Steele 1983). There have apparently been no measurements of NH_3 volatilization from unfertilized native ecosystems (Dawson 1977, Freney *et al.* 1983).

The objectives of this study were:

1. To measure ammonia volatilization rates in unfertilized grassland and forest ecosystems.
2. To contrast seasonal volatilization rates and determine the effects of soil temperature and water availability on these.
3. To compare ammonia volatilization rates among grassland and forest ecosystems and relate differences to environmental differences between those systems.

Ammonia losses were measured at two native grassland sites and two native forest sites. Because ammonia volatilization from unfertilized ecosystems is the result of complex generative and escape processes, an attempt was made to isolate the escape (volatilization) processes by applying a constant amount of NH_4 to a separate series of plots in each sampling period and determining the effects of season and site-specific factors upon loss of freely available NH_3 as outlined in objectives 2 and 3 above.

CHAPTER 2

LITERATURE REVIEW

Fundamental Reactions of Ammonia Volatilization

A scheme of reactions that represents ammonia volatilization is:

$$\text{Adsorbed NH}_4^+ \rightleftharpoons \overset{\overset{\text{Source}}{\downarrow}}{\text{NH}_4^+\text{(aq)}} \rightleftharpoons \overset{\overset{\text{Source}}{\downarrow}}{\text{NH}_3\text{(aq)}} \rightleftharpoons \text{NH}_3 \text{ (gas in soil)} \rightleftharpoons \text{NH}_3 \text{ (gas in atmosphere)} \qquad (1)$$

(Freney *et al.* 1983). The volatilization rate may be affected at any of the steps shown.

The equilibrium between NH_3 and ammonium in solution may be described by

$$NH_4^+ \underset{k_2}{\overset{k_1}{\rightleftharpoons}} NH_3 + H^+ \qquad (2)$$

(Avnimelech and Laher 1977). The reaction is dependent upon pH and temperature of the solution. There is an approximate tenfold increase in the relative concentration of NH_3 (aq) per unit increase in pH up to pH 9, and at pH > 11 all soluble ammoniacal N is in the form of NH_3 (aq) (Vlek and Stumpe 1978). Because the dissociation 'constant' of ammonium (k_1) increases with temperature, a large proportion of ammoniacal N appears as NH_3 (aq) at high temperatures (Freney *et al.* 1983).

The partial pressure (p_a) of ammonia gas in the soil air follows Henry's law, i.e.,

$$p_a = H_e A \qquad (3)$$

where A is the concentration of dissolved NH_3 and H_e is the Henry's law coefficient which increases with temperature (Danckwerts 1970, pp. 17-18). The concentration of NH_3 in the soil air remains constant at a given temperature and NH_3 concentration of the soil solution, but increases with high temperature and concentration of NH_3 in the soil solution. Volatilization of ammonia from solution is expected to occur in response to difference in vapor pressure between the solution and the ambient air (Denmead *et al.* 1982).

Sources of Volatilized Ammonia

Possible sources of ammonia for volatilization from natural ecosystems are recent additions, decomposition—by soil microbiota, plants and animals—and fires (Soderlund and Svensson 1976).

Microbial decomposition of soil organic nitrogen derived from plant litter, animal litter or residues of biological N_2-fixation, is an important source of the ammonia volatilized from natural ecosystems (Dawson 1977). The rate of such ammonification is primarily affected by temperature, water, and amount and nature of organic N present (Stanford and Smith 1972). The low temperature limit for most soil microbial activity is about 0°C, and Q_{10} is close to 2 for the temperature range from 5 to 35°C (Stanford *et al.* 1973). Ammonification rate is positively related to soil water potential in the range from permanent wilting point to field capacity (Stanford and Epstein 1974).

Volatilization of ammonia from aboveground parts of vegetation has been demonstrated by Denmead *et al.* (1978) and Farquhar *et al.* (1980). Such losses are likely to occur whenever temperature and stomatal conductance are high, and ambient partial pressure of ammonia is low (Farquhar *et al.* 1980).

Ammonia volatilization from animal waste is readily observed in densely grazed pastures and cattle feedlots, where substantial losses of gaseous NH_3, up to one-fourth of N deposited, have been measured (Denmead *et al.* 1974, Hutchinson *et al.* 1982). Animal excreta may also contribute to N loss by ammonia volatilization from grazed systems with low animal densities (Woodmansee 1978).

Terman (1979) and Beauchamp (1983) have reviewed the literature on ammonia volatilization from manures and sewage sludges applied to agricultural lands. Losses varied from 5 to over 90% of the nitrogen supplied.

Volatilization losses from ammoniacal fertilizers, such as anhydrous ammonia, urea, and various ammonium salts, have been reviewed by Terman (1979). Losses measured are variable, from negligible up to 50-60% of the applied N, depending on type of fertilizer, method of application, soil properties, season, weather conditions, and methods by which they are measured. While most studies of ammonia loss are related to losses from agricultural systems, a few deal with forest ecosystems (e.g., Mahendrappa and Ogden 1973, Craig and Wollum 1982).

Ammoniacal N recently added to ecosytems in rainwater or by dry deposition might also be volatilized. Ammonium concentrations in rainwater over the United States ranged from 0.01 to 1 mg l^{-1} and showed both geographical and seasonal variation (Junge 1958). Wet deposition in a particular area depends therefore on the amount of precipitation and how that is distributed over the year. Dry deposition of ammonia on a global scale has been estimated by Soderlund and Svensson (1976) to be of a similar magnitude to total wet deposition, but 60-90% of that is confined to the Tropics.

Factors That Affect Ammonia Volatilization

Most studies on factors that affect the volatilization process have been related to losses after application of ammonia fertilizers, but the same general principles should apply to NH_3 losses from unfertilized natural ecosystems.

Soil Factors

Many workers have studied the effect of soil pH on NH_3 volatilization from ammoniacal fertilizers (e.g., DuPlessis and Kroontje 1964, Watkins *et al.* 1972, Ryan *et al.* 1981).

The general conclusion is that NH_3 losses increase as pH rises. This is to be expected because much ammoniacal N is in ammonia form at high pH.

A hydrogen ion is released with each conversion of NH_4^+ to NH_3 so the medium tends to be acidified as a consequence of NH_3 loss. This results in a reduced fraction of ammoniacal N in the volatile $NH_3(aq)$ form. Thus, the ammonia volatilization capacity depends more on the presence of $CaCO_3$ or other soil buffers than on the initial pH of the soil solution (Avnimelech and Laher 1977, Vlek and Stumpe 1978).

Calcium carbonate has another effect on the loss of ammonia after ammonium salts are applied to soils (Fenn and Kissel 1973, 1975). Ammonium salts react with calcium carbonate to form calcium salts and unstable ammonium carbonate ($(NH_4)_2CO_3$) that decomposes readily to ammonia, water, and carbon dioxide. The importance of this mechanism for volatilization depends on the solubility of the calcium salt that is formed. If the solubility is low, as when ammonium sulfate, ammonium fluoride, and diammonium phosphate react with $CaCO_3$, the reaction is driven to formation of $(NH_4)_2CO_3$ and results in NH_3 volatilization. When soluble calcium salts are formed, as with ammonium nitrate, chloride, and iodide, equilibrium exists and there is little formation of $(NH_4)_2NO_3$ and therefore low rates of volatilization (Freney *et al.* 1983), i.e.,

$$2NH_4NO_3 + CaCO_3 \rightleftharpoons Ca(NO_3)_2 + (NH_4)_2CO_3 \qquad (4)$$

The NH_4^+ ion is adsorbed on cation exchange sites of soil particles. In soils with high cation exchange capacity (CEC), this results in reduced free ammonium and ammonia in the soil solution at a given pH and, consequently, less ammonia volatilization (Freney *et al.* 1983). A decrease in NH_3 as soil CEC increases has frequently been reported (e.g., Fenn and Kissel 1976, Daftarder and Shinde 1980, Ryan *et al.* 1981).

Climatic Factors

Soil moisture influences on ammonia volatilization are nonlinear. Volatilization is low in dry soils, high at intermediate moisture content and low again at high moisture levels (Fenn and Escarzaga 1976, Prasad 1976). Shimpi and Savant (1975) explain the low retention of ammonia in moist soils as a displacement of NH_3 molecules from sorption sites by water molecules. On the other hand, for a given amount of ammoniacal N in the soil, the concentration of NH_4^+(aq) is lower at high than low moisture levels. Therefore in wet soils, since the partial pressure of NH_3 in the air is dependent on NH_3(aq) concentration (Equation 3), a low NH_3 volatilization rate would be expected.

Simultaneous and contrary-wise capillary movement of water in wet soils helps transport ammoniacal N to the soil surface where it can be lost to the atmosphere (Fenn and Kissel 1976). A direct relationship between NH_3 loss and evaporation of water has been shown by Denmead *et al.* (1976) and Fenn and Escarzaga (1977).

Ammonia volatilization increases with temperature (Fenn and Kissel 1974, Prasad 1976, Vlek and Stumpe 1978). At high temperatures the ammonium-ammonia equilibrium in the soil solution (Equation 2) is shifted to the formation of ammonia and the solubility of ammonia in water is reduced (Equation 3). Evaporation of water and capillary transport rise with temperature. Temperature and moisture content also affect rates of biological uptake-release processes, which influence the amount of ammoniacal N present in the soil.

Wind affects the rate of ammonia volatilization by directly transporting NH_3(aq) from the soil surface, lowering the partial pressure of the gas there, and, hence, promoting net upward diffusion (Freney *et al.* 1983, Simpson and Steele 1983). A positive relationship between wind velocity and ammonia loss was demonstrated by Watkins *et al.* (1972), Freney *et al.* (1981) and Denmead *et al.* (1982).

Biotic Factors

Biotic factors that influence the amount of ammoniacal N in the soil and therefore NH_3 volatilization may be positive (ammonification and urea hydrolysis) or negative (uptake of NH_4^+ by plants or soil microorganisms (Rosswall 1976) and nitrification).

Hydrolysis of urea is catalyzed by the enzyme urease which is widely distributed in plants, microorganisms, and soils. Urease activity is related to organic matter content, soil texture, soil temperature, soil moisture and soil pH (Freney *et al.* 1983).

In well-aerated soils most of the NH_4^+ derived from mineralization of organic matter is either immobilized by microorganisms or plants, or oxidized to NO_3 as rapidly as it is formed (Schmidt 1982). Under most tilled soil conditions, nitrification is limited by ammonium availability (Russell 1973, pp. 332-333), but it is more sensitive than ammonification to extreme temperatures, extreme moisture contents, or pH below neutral (Alexander 1965, Schmidt 1982, Tyler *et al.* 1959). Under conditions where nitrification rate is reduced more than the decomposition rate, as in soils that are wet and colder than 5-10°C, or in dry soils with water potential in the -15 to -30 bars range, an increase in ammoniacal N levels may result (Campbell *et al.* 1970, Russell 1973, Schmidt 1982, Tyler *et al.* 1959). The effect of nitrification on ammonia evolution has been demonstrated with measurements of much greater NH_3 volatilization when a nitrification inhibitor was applied with ammoniacal fertilizer than when the fertilizer was applied alone (Cornforth and Chesney 1971).

CHAPTER 3

MATERIALS AND METHODS

The Ammonia Absorbing Device

The ammonia absorption equipment used was modeled after equipment described by Volk (1959). The trap was a 75 ml bottle, with an inside diameter of 4.1 cm and an outside diameter of 4.8 cm, containing 10 ml of 0.1 N sulfuric acid. The trap was placed directly on the soil surface, with a wire-mesh screen on top to exclude insects. The bottle was covered with a 800 ml cylindrical, plastic chamber which was 11.1 cm in diameter and 11 cm high. The edges of the chamber were sealed to the ground with sand to reduce air exchange between its interior and the outside. A brick was placed on top to keep the assembly in place.

The absorption surface of the ammonia trap was 13.2 cm^2, and the emission surface, i.e., the area inside the plastic chamber, 96.8 cm^2. It was assumed that the area under the trap was an active emission surface. If none of it was, the calculated loss should be corrected upward by a factor of 1.23.

Ammonia traps were set out for seven day-periods. After that, the brick and the plastic container were carefully removed and the trap was closed with its lid. Samples were neutralized with 1 ml of 1 N NaOH immediately before determination of ammoniacal N by the phenate method (American Public Health Association 1980, pp. 360-361). The principle of the method is a formation of indophenol blue by a reaction of ammonia, hypochloride and phenol catalyzed with a manganous salt. The intensity of the blue color was measured with a Spectronic 20 spectrophotometer. A blank and a series of standards from

0.1 to 10 μg NH_4^+-N per 11 ml were carried through the procedure with samples from each collection period. Any samples that were visually contaminated with insects, sand, etc., were excluded from the results.

The bottles, their lids and all glassware used were soaked overnight in dilute sulfuric acid and rinsed with distilled water, just before each use, to prevent contamination with atmospheric ammonia. The plastic chambers were also washed with dilute acid and rinsed with distilled water prior to each use.

Site Descriptions

The four study sites chosen represent a range of habitats from semiarid grasslands to moist conifer forests. All the sites are in Gallatin County, Montana. Climatic data are listed in Table 1. Common species at all sites are listed in Appendix Table 11. Some soil characteristics are presented in Table 2. Soil reaction (pH) was measured in a paste with a soil:water ratio of 1:2; cation exchange capacity (CEC) was determined with an ammonium saturation method (Chapman 1965); calcium (Ca) was measured with ammonium acetate (Bower *et al.* 1952); and percent organic matter (OM) was determined with a simplified colorimetric method (Sims and Haby 1970). Soil classification for all the sites except the ABLA site (p. 12) are based on DeYoung and Smith (1931) and Montagne *et al.* (1982). Following is a brief description of each site.

The site designated as the BOGR site in this paper is in a *Stipa comata/Bouteloua gracilis* grassland habitat type (Mueggler and Stewart 1980). The site is 1.2 km west of Logan. The elevation is 1280 m and the site has a slight (1-2%) southern aspect. The soils are classified on a subgroup level as Typic Calciborolls. Ground cover as measured by a step-point method (Evans and Merton 1957) was: 10% bare ground, 17% cryptogam, 40% *Bouteloua gracilis*, 21% *Stipa comata*, 6% other grasses and 6% forbs and shrubs.

Table 1. The Monthly Average Temperature and Precipitation for Weather Stations Near the Study Sites.*

Month	Year	Trident (BOGR) T	Trident (BOGR) P	Belgrade Airport (AGSP) T	Belgrade Airport (AGSP) P	Bozeman 12NE (PSME & ABLA) T	Bozeman 12NE (PSME & ABLA) P
June	1982	16.2	89	14.2	109	9.6	108
July	1982	20.3	18	18.2	31	13.7	68
August	1982	20.9	20	19.8	30	14.7	57
September	1982	13.1	64	12.0	46	7.8	122
November	1982	-1.3	9	-4.9	9	-4.5	51
December	1982	-4.2	14	-8.4	22	-6.5	62
January	1983	-0.1	1	-2.0	2	-2.4	32
February	1983	2.2	3	0.3	7	-2.9	46
March	1983	4.1	11	2.9	18	0.4	68
April	1983	4.3	13	3.8	41	0.9	61
May	1983	11.6	36	9.4	44	5.3	100

*(USDC 1982-1983).

T = Mean monthly temperature (°C).

P = Cumulative precipitation per month (mm).

Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

Table 2. Some Characteristics of Soil Samples Taken From 0-10 cm at the Study Sites.

Site		pH	CEC	Ca	OM
			--------meq/100 g	----------	% of soil
Grassland	BOGR	7.8	20.2	37.7	2.5
	AGSP	7.6	19.4	12.0	3.4
Forest	PSME	6.6	37.2	21.0	4.7
	ABLA	6.7	29.6	20.3	6.9

(pH, CEC, Ca and OM are under the spanning header "Soil Characteristics*".)

*Numbers are mean of 3 replicates for pH, Ca, and OM; 2 replicates for CEC.

Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

The AGSP site is in an *Agropyron spicatum/Bouteloua gracilis* grassland habitat type (Mueggler and Stewart 1980). The site is 2.5 km southeast of Belgrade on level land at 1360 m elevation. The soils are Typic Argiborolls (Beaverton series). Ground cover measured by step-point method was: 9% bare ground, 11% cryptogam, 30% *Agropyron spicatum*, 15% *Bromus tectorum*, 12% other grasses and 24% forbs.

The site designated as the PSME site in this paper is in a *Pseudotsuga menziesii/Carex geyeri* forest habitat type (Pfister *et al.* 1977). It is 19 km northeast of Bozeman on Route 86 approximately 100 m north of the Bridger Bowl intersection of the Bridger Canyon highway. The site has 4% southwest aspect at 1870 m elevation. The soils are classified as Argic Cryoborolls. The understory at the site is dominated by *Carex geyeri* while the principle overstory vegetation is *Pseudotsuga menziesii* with some *Pinus contorta*. Climatic data for the PSME site, as for the other sites, are presented in Table 1. The Bozeman 12NE, the representative weather station for this site, is situated in a low area into which cold air can drain. Actual temperatures at the PSME site are likely to be higher than at 12NE because of PSME's southern aspect.

The ABLA site is in an *Abies lasiocarpa/Vaccinium scoparium* forest habitat type (Pfister *et al.* 1977). It is located 19 km northeast of Bozeman about 1.0 km north of the Bridger Bowl ski area. The elevation is 1870 m and the site is situated on a slight north facing slope (1%) at a valley bottom. The soils are classified as Mollic Cryoboralfs (Weaver and Forcella 1975). The understory is dominated by a patchwork of *Carex geyeri* and *Vaccinium scoparium*. The overstory is governed by *Abies lasiocarpa* but also contains a few *Pinus contorta*. The transects were placed in the *Vaccinium* dominated areas.

Field Procedure

The ammonium trapping devices were placed on two transects at each site. Each 30 m transect had ten traps at 3 m intervals. The fertilized treatment was applied on one of the transects; the other was left undisturbed. The two treatments are called 'fertilized' and 'unfertilized' respectively. Fertilizing was done by dripping 1 ml of ammonium nitrate solution (0.048 gNH_4^+-N ml^{-1}) on the area under the plastic container when the traps were put out. The fertilization rate represented 50 kg of NH_4^+-N ha^{-1}. One site (PSME) had four 15 m long transects, since it was impossible to use 30 m long transects due to lack of level space. Controls used to estimate the 'background noise' of the method were placed at both ends of each line. Those were set up and run exactly as the ammonia absorbing devices, except that all contact with the soil surface was eliminated by putting a tight fitting lid on the plastic container. At the end of the seven day collection period, all the containers were removed. At each successive collection period the ammonia absorbing devices were moved along the transect approximately 30 cm from the last site, so the measurements would not be influenced by earlier measurements.

When there was snow on the ground, the snow cover of a small area was removed, the traps were placed on the ground and covered with snow.

Soil temperature was recorded with a maximum-minimum thermometer at 10 cm depth at each site. Soil potential was measured at two depths, 10 and 25 cm, at each site. This was done with porous gypsum (plaster) blocks, and three replicates were used at each site.

Efficiency of Method

Closed systems for measuring ammonia volatilization—like the one used in this study —probably underestimate the actual amount of ammonia that is evolved, due to alteration of the microenvironment and to inherent trap characteristics (Beauchamp *et al.* 1978, Denmead 1983). First, a microenvironment is created within the enclosures that is somewhat different from the natural microenvironment at the surface of the sites. The effects of small differences in temperature and moisture are difficult to assess but the total elimination of wind could reduce volatilization (Nommik 1973). Second, because ammonia is highly reactive and readily soluble in water it could be retained in any condensates on walls of the enclosure (Denmead 1983). It is also possible that the uppermost layers of the acid in ammonia traps could become temporarily saturated with dissolved gas, thereby slowing their absorption rate, especially at subzero temperatures when the dilute acid in the ammonia traps is frozen. At low temperatures, absorption might also be reduced because of lowered diffusion rates.

No effort was made to estimate complex microenvironmental effects. However, the efficiency of the ammonia traps with regard to chemical and physical properties of traps and gas were estimated by measuring the percent of a known quantity of ammonia introduced which was absorbed by the traps under laboratory conditions. The experiment was carried out for 7 days over the entire temperature range experienced in the field (i.e., -14, 22, and 40°C). The apparatus was the same as for controls, i.e., there were tightly fitting lids on the plastic chambers which contained the acid bottle and a dish, 4.5 cm in diameter, holding 1 ml of an ammonium hydroxide-ethyl alcohol solution. Five concentrations of ammonium hydroxide were tested: 0, 3, 10, 100, 300, and 1000 μgN ml^{-1}. Five replications of each treatment were used. The mean amount of ammonia in controls for each temperature treatment was subtracted from ammonia in samples from that treatment before their recovery was calculated.

Data Analysis

To determine whether ammonia was emitted, the mean quantity of ammonia measured in samples was compared with the mean quantity measured in the controls for that site and collection period. The population variances of the controls and the treatments were, in most instances, significantly different, making an ordinary t-test not applicable. A similar test not requiring equal variances was therefore applied instead (Snedecor and Cochran 1980, pp. 96-98).

To relate ammonia loss to seasonal conditions, ammonia loss was regressed against soil temperature, water potential, or season on a site-by-site basis.

To relate ammonia loss to site conditions, ammonia loss was regressed against water potential, soil temperature, organic matter content, soil reaction (pH), cation exchange capacity (CEC), and calcium (Ca) concentration, on data combined across all sites.

All ammonia losses discussed are ammonia measured in traps, minus mean ammonia in controls, for that site and collection period.

CHAPTER 4

RESULTS

Ammonia Losses From Unfertilized Plots

NH_3-N losses from undisturbed grasslands and forests tended to be greater in the spring and early summer than in late summer and winter (Fig. 1, Appendix Table 6).

At the BOGR grassland site, ammonia loss was not statistically significant during collection periods in July and late August, 1982, but was 8.2 μgN m^{-2} day^{-1} during the mid-August measurement. Losses were low (less than 5 μgN m^{-2} day^{-1}) but significant during the winter sampling periods—October 1982 to March 1983—and increased again during the April and May 1983 sampling periods with the highest losses of 15.7 μgN m^{-2} day^{-1} being measured in May.

Losses from the AGSP grassland site showed similar trends. Losses in July and mid-August 1982 were significant but low. During the October 1982 collection period there was a high loss of 12.2 μgN m^{-2} day^{-1}. Losses were low but usually significant between November 1982 and March 1983. Losses increased again in the spring with the highest loss rates being measured in May 1983, almost 25 μgN m^{-2} day^{-1}.

NH_3-N losses from the forest sites were generally lower than from the grassland sites. The only significant loss measured at the PSME site was recorded in late August 1982 (8.7 μgN m^{-2} day^{-1}).

The ABLA site showed significant loss during four collection periods: July, mid-August, and October 1982, and May 1983. The highest loss measured was 8 μgN m^{-2} day^{-1} in mid-August.

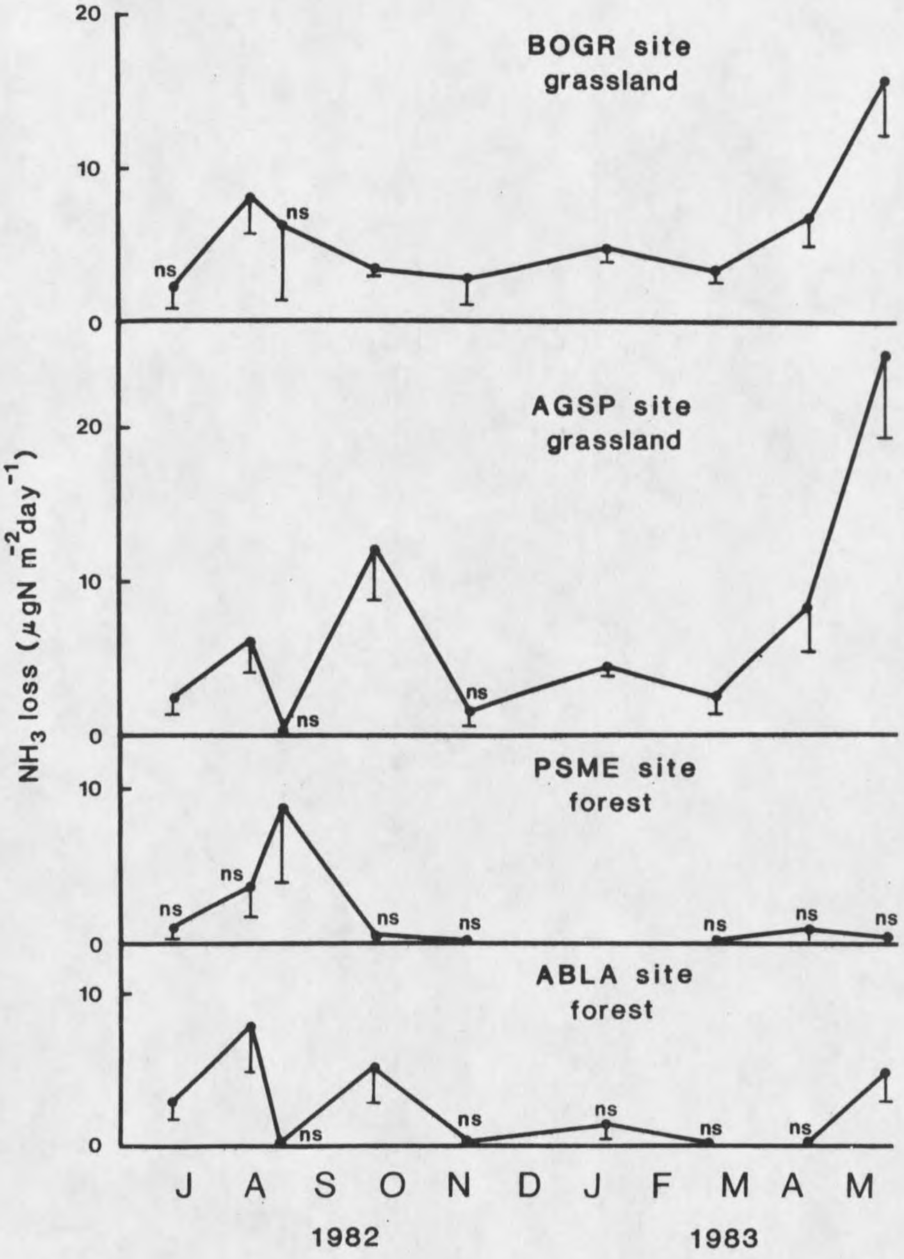

Figure 1. Ammonia volatilization from unfertilized plots averaged over one week. Cases when volatilization was not significant at 0.1 level are indicated by ns. There was no sampling at the PSME site in January 1983. Vertical bars show S.E. Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

Ammonia Losses From Fertilized Plots

Losses from fertilized plots were high in the summer and fall, low during the winter, and high again in the following spring.

At the grassland sites (Fig. 2 and Appendix Table 6) NH_3-N losses were always significant at the 0.1 level, but only a small proportion of the NH_4^+-N applied to each plot (corresponding to 50 kgNH_4^+-N ha^{-1}) was recovered during the week long sampling period. The maximum losses were 2476 μgN m^{-2} day^{-1} in late August 1982 at the BOGR site and 1189 μgN m^{-2} day^{-1} for the same sampling period at the AGSP site. Losses from fertilized plots were 2 to 3 orders of magnitude higher than from unfertilized plots in the summer. Differences were much smaller during the winter when losses from unfertilized plots were almost equal to losses from fertilized plots. In May 1983, losses from unfertilized actually exceeded losses from fertilized plots at the AGSP site. Losses from fertilized plots were always higher at the BOGR than at the AGSP grassland site; most often they were more than 2 times higher.

The pattern of loss from fertilized plots at the two forest sites was almost identical (Fig. 2 and Appendix Table 6). The highest loss rates were measured in mid-August 1982 and were 85 and 87 μgN m^{-2} day^{-1} for the PSME and ABLA sites, respectively. Losses of fertilizer nitrogen were low or not significant during the winter. Maximum losses from the forest sites were more than an order of magnitude lower than maximum losses from either grassland site.

Soil Water and Temperature Conditions

Measurements of water potential and soil temperature at 10 cm depth are presented in Figure 3 and Appendix Table 7. The temperature presented in Figure 3 is an average of the maximum and minimum temperature readings at a 10 cm depth. The average temperature ranged from −5 to 27.5°C with greater range observed for the grassland sites than the

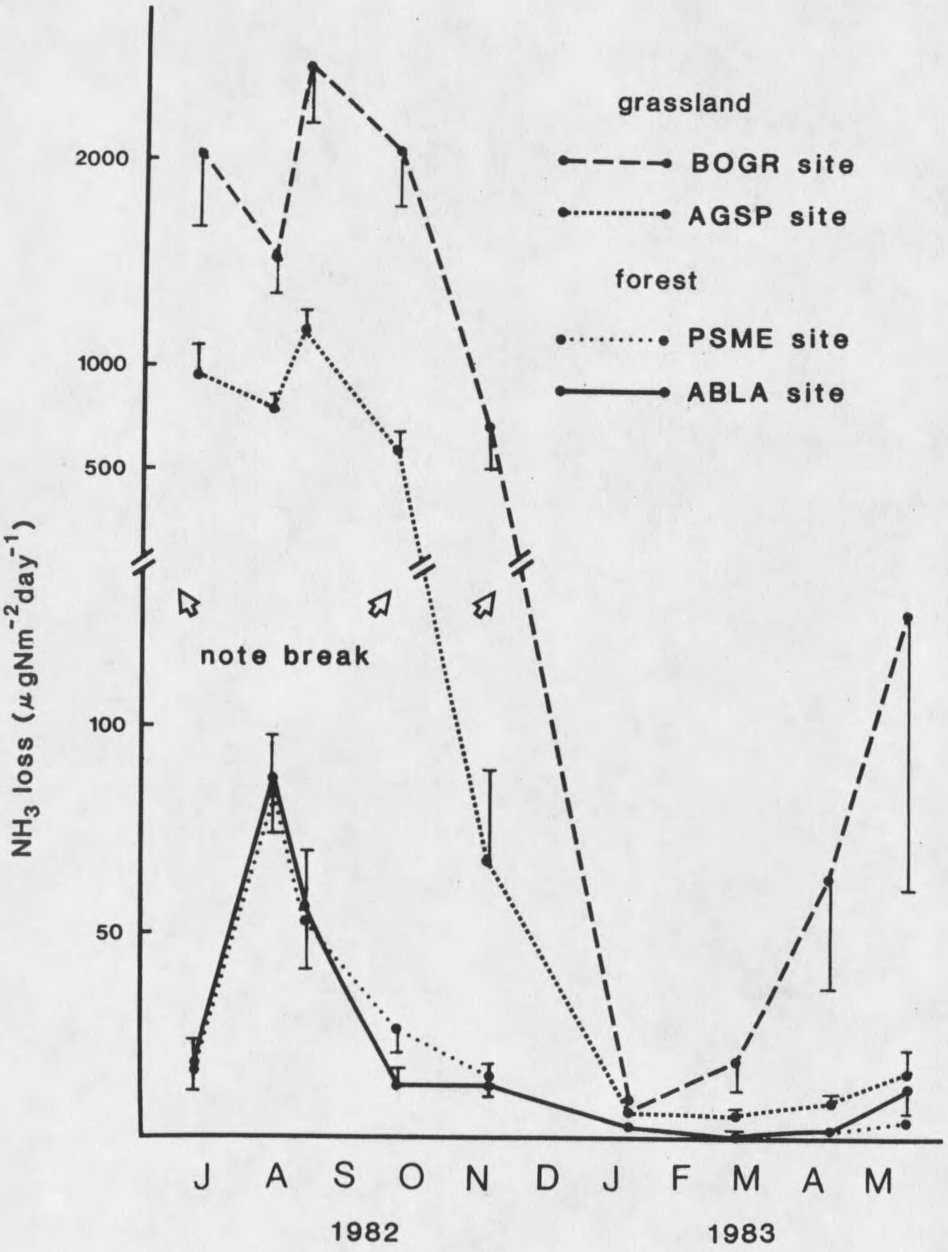

Figure 2. Ammonia volatilization from fertilized plots (50 kg NH_4^+-N ha^{-1} of NH_4NO_3) averaged over the first week after application. Volatilization was significant at 0.1 level in all cases except for in April 1983 at the PSME site, and January and March 1983 at the ABLA site. There was no sampling at the PSME site in January 1983. Vertical bars show S.E. Note break and change in vertical scale. Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

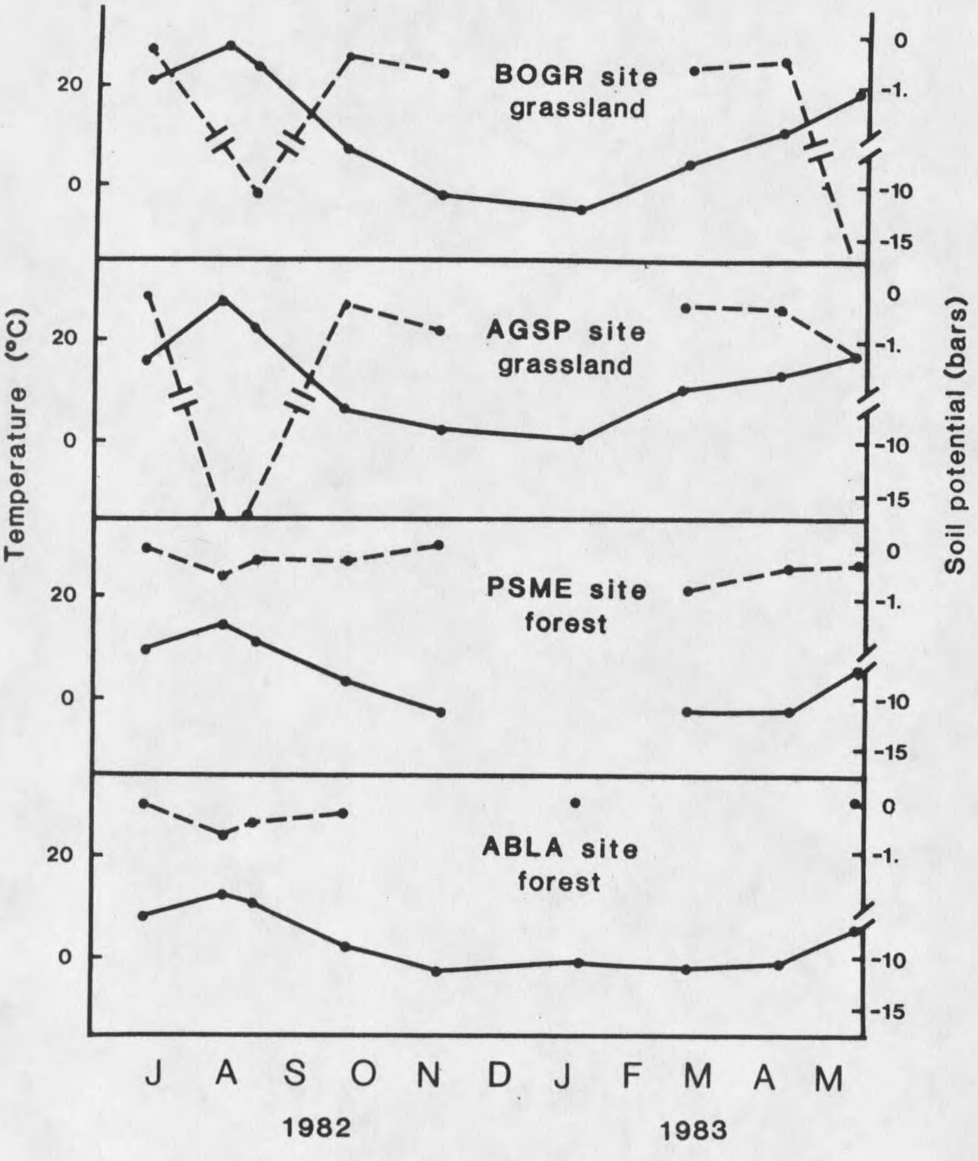

Figure 3. Soil temperature (•———•) and water potential (•-----•) at 10 cm during sampling periods. Note break and change in right vertical scale (water potential). Data points for water potential are missing at the grassland sites in January 1983 because the soil was frozen (i.e., very dry), and at the ABLA site during winter because the gypsum blocks were inaccessible due to snow and ice. Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

forest sites. The water potential data indicate that the soil at the grassland sites was dry during midsummer (−10 to −20 bars) and was never saturated for extended periods. Water stresses at the forest sites were significantly less; the water potential was always between 0 and −0.8 bars.

The soil water potentials at 25 cm were very similar to those measured at 10 cm. The following discussion is based only on the water potential measurements made at the 10 cm depth, but the water potentials measured at the 25 cm depth are presented in Appendix Table 7.

Correlations of NH_3-N Loss With Water Potential and Soil Temperature Within Each Site

Correlation coefficients between NH_3-N loss and soil temperature, water potential and season are summarized in Table 3. There was a positive relationship between NH_3-N loss from both unfertilized and fertilized plots at all sites and soil temperature; i.e., the warmer it was the higher the ammonia evolution. The correlations between NH_3-N loss from unfertilized plots and soil temperature were generally lower than the correlations between fertilized plots and soil temperature. The highest correlations between loss from fertilized plots and soil temperature was at the forest sites ($r \geqslant 0.8$).

At all the sites, except the AGSP grassland, there was a negative relationship between NH_3-N loss from unfertilized plots and water potential. There was also a negative relationship between NH_3 loss from fertilized plots and water potential at all sites; i.e., the more water there was available, the lower the NH_3-N loss. The largest correlation was for loss from fertilized plots at the ABLA forest site ($r = -0.924$). Although the range of water potential measured at that site was only from −0.6 to 0 bars, this represents a large difference in moisture content of the soil (probably twofold).

Table 3. Correlation Coefficients Between NH_3 Loss and Soil Temperature at 10 cm, Water Potential at 10 cm, and Season[1].

		Dependent Variable	
Site[2]	Independent Variable	NH_3-N Loss From Unfertilized Plots	NH_3 Loss From Fertilized Plots
		r	
BOGR	temperature	0.334	0.546
	water potential	-0.795*	-0.054
	season	-0.036	0.773**
AGSP	temperature	0.192	0.609
	water potential	0.271	-0.655
	season	0.023	0.818**
PSME	temperature	0.573	0.796*
	water potential	-0.040	-0.152
	season	0.394	0.704**
ABLA	temperature	0.581	0.850**
	water potential	-0.542	-0.924**
	season	0.585	0.720*

[1] Value of season is assigned with respect to month during which measurements were made; i.e., 1: January, February; 2: December, March; 3: November, April; 4: October, May; 5: September, June; 6: August, July.

[2] Sites are characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

*,**Significance at the 0.05 and 0.01 probability levels respectively.

Significant positive relationships between NH_3-N loss and season were observed on all the fertilized plots ($r > 0.7$); losses were low in the winter and higher during the summer. The same trend can be seen for losses from unfertilized plots at forest sites, but at the grassland sites the effect of season is not demonstrated ($|r| < 0.05$).

Correlations of NH_3-N Loss With Selected Soil Characteristics Across Sites

Correlations of NH_3-N losses (combined data from all sites) with soil temperature and water potential (Table 4) show trends similar to those observed within sites across seasons: ammonia evolution increases with temperature and decreases with increasing soil water. NH_3-N losses from unfertilized plots at all sites were weakly correlated ($|r| \leqslant 0.4$)

with soil characteristics (pH, CEC, Ca, and OM), but stronger correlations were observed with losses from fertilized plots (|r| from 0.43 to 0.54). There was less NH_3-N evolution from soils with higher CEC and organic matter (negative correlation), but more evolution from increasingly basic soils (positive correlation with pH). NH_3-N losses from fertilized plots were significantly correlated with calcium concentrations in the soil, but there was no such correlation with losses from unfertilized plots.

Table 4. Correlations of NH_3-N Loss With Selected Soil Characteristics Across Sites.

Soil Parameters	NH_3 Loss From Unfertilized Plots	NH_3 Loss From Fertilized Plots
	r	
soil temperature	0.441*	0.557**
water potential	-0.243	-0.422**
pH	0.396*	0.543**
CEC	-0.407*	-0.461**
Ca	0.003	0.431**
organic matter	-0.312	-0.502**

*,**Significance at the 0.05 and 0.01 probability levels.

Test of Trap Efficiency

Recovery of ammonia in the efficiency test is presented in Table 5. In traps kept at subzero temperatures (-14°C) and where little NH_4OH (3 μgN) was introduced little of the ammonium introduced was recovered. Recovery was higher where 100 and 200 μgN were introduced (about 70%) and highest at 1000 μgN. The increased recovery with increasing nitrogen additions suggest that some ammonia may have been absorbed on the walls of the absorption chamber, proportionally more when ammonium concentrations were low than when they were high. The high recovery rate (93%) for the subzero temperature treatment and the largest N introduction (1000 μgN) suggests that saturation of the surface layer of acid in traps did not significantly reduce recovery.

Table 5. Percent Recovery of Introduced Ammonia in Traps Tested Under Laboratory Conditions.

	μgN Introduced				
Temperature	3	10	100	300	1000
°C	% recovered[1]				
-14	0	44 + 6*	70 + 4	77 + 2	93 + 2
22	46 + 7	92 + 7	74 + 3	77 + 3	84 + 4
40	56 + 10	63 + 3	77 + 4	66 + 3	91 + 2

*+ S.E.

[1] % recovered $= \dfrac{\text{ammonia in sample} - \text{ammonia in controls at that temperature}}{\text{ammonia introduced}} \times 100$

The efficiency of traps should be considered when interpreting the field measurements. Since most samples obtained from unfertilized plots and some of the samples from fertilized plots yielded amounts of ammonia similar to or less than those used in the smallest addition in the efficiency test (3 μgN), actual spring and summer NH_3-N evolution rates could be twice those reported. Maximum yields of samples from fertilized plots in the summer was similar to yields from the 300 μgN application rate so actual NH_3-N evolution rates could be 1.3 to 1.5 times those reported.

CHAPTER 5

DISCUSSION

Rates of Ammonia Losses

NH_3-N losses from unfertilized plots (Fig. 1) were measurable at all the study sites during one or more sampling periods. Statistically significant losses ranged from 2.5 to 25 μgN m^{-2} day^{-1}. Losses from fertilized plots (Fig. 2) were significant during most sampling periods and were usually higher than losses from unfertilized plots. On the fertilized plots loss was always a small proportion of the applied NH_4^+-N; the largest loss measured during the first week after application was 0.35% of the applied NH_4^+-N (50 kgNH_4^+-N ha^{-1}) at the BOGR grassland site in mid-August 1982.

The NH_3-N losses measured in the present study may underestimate actual ammonia volatilization for two reasons. First, the efficiency of ammonia traps was less than 100% based on a laboratory test (Chapter 4, Test of Trap Efficiency). The trap efficiency was estimated to be about 50% for the lower levels of ammonia losses measured from unfertilized plots, and 50-70% for losses measured from fertilized plots. Second, alteration of the microenvironment within the absorption chambers may have reduced NH_3-N losses from the soil. While temperature and moisture effects were probably small, exclusion of wind could have had significant effects. For example, up to fivefold faster depletion of ammonia —due to volatilization—from solution has been reported under windy conditions than under no wind conditions (Folkman and Wachs 1972, Bouwmester and Vlek 1981). The exclusion of wind effects on unfertilized plots at forest and grassland sites is however expected to have little significance because the concentration gradient of NH_3-N from soil solution to the air is not steep. No effort was made to estimate effects of wind exclusion, since neither NH_3 concentration in the soil solution, nor NH_3 concentration in the ambient air, nor rate of windflow near the soil surface were measured, but it is doubtful that escape of NH_3-N from the soil surface was reduced by more than factor of 2. Tendency to underestimate should be less in forests than grasslands because of naturally less windflow, and that wind movement which does occur is at a minimum speed.

Seasonal Variation in NH_3-N Evolution and Relation to Water Potential and Soil Temperature

Rates of ammonia losses at grassland sites were highest in spring, 15.7 and 24.6 μgN m^{-2} day^{-1} at the BOGR and AGSP sites respectively (Fig. 1). Loss rates varied from nonsignificant to about 8 μgN m^{-2} day^{-1} during the summer, and were low ($<$ 5 μgN m^{-2} day^{-1}) but still mostly significant during the winter. Similar trends were observed at forest sites but losses were significant only in spring and summer; maximum losses were 9 μgN m^{-2} day^{-1}.

Ammonia losses from fertilized plots were well correlated ($r > 0.7$) with season at all sites. Losses were high in the summer, but low during the winter. Maximum losses from fertilized plots during the summer were 2476, 1189, 85, and 87 μgN m^{-2} day^{-1} for the BOGR, AGSP, PSME, and ABLA sites respectively. Minimum losses during winter at all sites were less than 10 μgN m^{-2} day^{-1}. Losses from fertilized plots were probably primarily a function of the conditions for the volatilization processes since ammoniacal N supplies were large and nearly constant. This is because a constant amount of NH_4^+-N was added to the fertilized plots at the beginning of each sampling period, and only a small fraction of it was volatilized as NH_3 ($<$ 1%), so the amount of ammoniacal N at the plots was nearly constant during the week-long sampling period. As losses from fertilized plots at all sites were correlated with season, it may be concluded that conditions were favorable for volatilization during summer sampling periods, but less favorable during winter sampling periods.

In contrast, losses from unfertilized plots were functions of both the volatilization processes and the availability of ammoniacal N in the soil. Losses from unfertilized plots showed weaker seasonal trends than losses from fertilized plots, and at the grassland sites losses were deficient in summer and fall. This suggests that losses are limited in summer and fall by ammoniacal N supply in the soil. Ammoniacal supply is regulated via inputs (mineralization and ammoniacal deposition), and outputs (immobilization by plants and microorganisms, nitrification, and volatilization).

Ammonia losses were always positively related with soil temperature, i.e., high losses were associated with high soil temperatures (Table 3). Correlations between temperature and loss from unfertilized plots were low ($r < 0.6$) but they were higher on fertilized plots, especially at the forest sites ($r \geqslant 0.8$). Increased ammonia volatilization at higher temperatures may be due to increased dissociation of NH_4^+ (Equation 2)), decreased solubility of NH_3 in solutions at higher temperatures (Equation 3), and increased rate of diffusion.

Ammonia losses were negatively correlated with soil water potential (Table 3), i.e., losses were greater in dry soils except on unfertilized plots at the AGSP site. The relationship between NH_3-N losses and water potential was weak, but was stronger on fertilized plots than on unfertilized plots. The high losses observed in dry soils may be due to increased concentration of ammoniacal N in soil water as the soil dries and to the rise in diffusion path (pore space) as the soil dries and it occurs in spite of the high retention of ammonia that is expected in very dry soils (Shimpi and Savant 1975, Prasad 1976). It should, however, be kept in mind that there were high negative correlations between soil temperature and water potential at all sites ($r < -0.7$, Appendix Table 9) except the PSME forest site (r = –0.009). Both forest sites showed significant relations between NH_3-N loss from fertilized plots and temperature. Losses were strongly correlated with water potential at the ABLA forest site (r = –0.927), but only weakly correlated at the PSME site (r = –0.152). Since the two forest sites otherwise had similar characteristics, one might deduce that soil temperature had more influence on NH_3-N volatilization than soil water did. This may also apply for the grassland sites.

The correlations between losses from unfertilized plots and either soil temperature or soil water potential were usually lower than corresponding correlations with loss from fertilized plots. This probably occurs because N loss from unfertilized plots involves not only the volatilization process but also ammoniacal N releasing and binding processes and so involves water and temperature in more, sometimes counter-productive ways and may involve other seasonably variable factors (e.g., substrate availability) as well.

Differences in NH_3-N Losses Among Sites, and Their Relation to Soil Characteristics

Ammonia volatilization from unfertilized plots was similar at all sites during summer (Fig. 1). During winter volatilization was significant in the grassland sites, but insignificant in forest sites. In spring volatilization was 4 to 6 times higher in grassland sites than in the ABLA forest site; volatilization was insignificant in the PSME site.

Volatilization from fertilized plots was usually two times higher at the BOGR grassland site than the AGSP grassland site (Fig. 2). Volatilization from fertilized plots on forest sites was 2 to 3 orders of magnitude lower than volatilization from fertilized plots on grassland sites during summer, but differences among sites were less in the winter.

These differences among sites were probably due to differences in organic substrates, climatic characteristics, and soil characteristics. In an attempt to understand the differences, NH_3-N losses from all sites were regressed against soil temperature, water potential, and soil characteristics for which controlling roles could be hypothesized (pH, cation exchange capacity, calcium concentration, and organic matter content, Table 4). Since these soil characteristics are related to each other (Appendix Table 10) correlations between them and NH_3-N volatilization must be interpreted with great care, and though causes may be suggested, none are proven.

NH_3-N losses from both fertilized and unfertilized plots were possibly correlated with soil temperature and negatively correlated with water potential just as they were when losses were related to changes across season in soil climate on a site-by-site basis. This is probably due to effects on the supply and volatilization processes as discussed earlier.

The positive correlation between NH_3-N volatilization and pH is probably due to the shift of NH_4^+ - NH_3 equilibrium in the soil solution towards NH_3 at higher pH values (Equation 2).

The negative correlation with cation exchange capacity may be due to increased absorption of NH_4^+ on cation exchange sites and the corresponding reduction of NH_4^+ in the soil solution (Chapter 2, Soil Factors).

The relatively strong negative correlation between organic matter content and NH_3-N losses is difficult to explain, except in terms of its negative relationship with pH and positive relationship with cation exchange capacity (Appendix Table 10).

While on unfertilized plots there was no relationship between NH_3-N losses and calcium concentration in the soil, on fertilized plots there was a significant correlation between losses and the calcium concentration. For example, calcium concentration is three times as high at the BOGR site as at the AGSP site, but the soil characteristics at the two grassland sites are otherwise similar, and NH_3-N losses from fertilized plots can be twice as large at BOGR as at AGSP. This difference in calcium concentration could explain higher losses from fertilized plots at the BOGR site in two ways. First, most of the calcium is probably in the carbonate form, and if so the different $CaCO_3$ contents will reflect different buffering capacities of the soils and therefore their abilities to resist acidification (i.e., decreasing pH) resulting from NH_3-N volatilization (Chapter 2, Soil Factors). Second, the higher the $CaCO_3$ level in the soil, the more $(NH_4)_2CO_3$—from which NH_3 is easily volatilized—is formed before equilibrium is reached (Equation 4).

Differences between sites in rates of ammonia losses from fertilized plots probably reflected differences in their retention capacities since fertilization made ammonium approximately equally available on all sites. These rates declined from BOGR to AGSP to PSME to ABLA.

Between-site differences in losses from unfertilized plots could reflect differences in retention capacities and/or differences in ammoniacal N availability. Losses from the fertilizer experiment demonstrate the differences in retention capacity. Data from grasslands (*Festuca idahoensis* and *Festuca idahoensis/Artemisia tridentata)* and forests (PSME and ABLA) of the area (Weaver and Forcella 1979) suggest that there are parallel differences in ammoniacal N availability, i.e., that ammonia is more available in grassland than in forest soils.

Estimates of Annual NH_3-N Losses From Undisturbed Grasslands and Forests

To roughly estimate the total NH_3-N losses per year, the year was divided into four periods: January through March, April through June, July through September, and October through December, and mean losses per day for each period were calculated by averaging all measurements that fell under that period (nonsignificant losses were set equal to zero). Mean losses per day were multiplied by 91 to get total losses for each period and these were summarized across the four periods. The resulting total losses for one year were 19, 26, 2.5, and 8 gN ha^{-1} yr^{-1} for the BOGR, AGSP, PSME, and ABLA sites respectively.

If these estimates are multiplied by two to correct for trap inefficiency, loss rates become 38, 52, 5, and 16 gN ha^{-1} yr^{-1} for BOGR, AGSP, PSME, and ABLA sites respectively. Considering the low concentration gradient from the soil solution to the air that is expected on undisturbed plots (Chapter 5, Rates of Ammonia Losses), a second factor of two will probably over-correct for any effect of reduced wind flow. If so, actual ammonia losses are probably less than 76, 104, 10, and 32 gN ha^{-1} yr^{-1} at BOGR, AGSP, PSME, and ABLA sites respectively.

No account of earlier measurements of ammonia volatilization from undisturbed natural ecosystems was found in the literature. Simulation of ammonia volatilization from undisturbed land by Dawson (1977) yielded average annual volatilization of 3400 gN ha^{-1} for all land areas between 40 and 50 N latitude which is two orders of magnitude higher than the measurements presented here even if they are corrected for trap inefficiency and microclimatic effects.

These data suggest that NH_3-N is lost more rapidly from dry grasslands than from coniferous forests. The differences suggested may well be an underestimate of actual differences since losses were measured at ground level. Absorption of ammonia by plant canopies has been reported by some workers (Denmead *et al.* 1976, Farquhar *et al.* 1980), and while most of the ammonia leaving the soil surface in a dry grassland should pass through the sparse vegetation to the atmosphere, much of the NH_3 leaving the soil surface in a forest may be absorbed as it passes through successive canopy strata (Mahendrappa 1975).

CHAPTER 6

CONCLUSIONS

Ammonia volatilization from undisturbed grasslands and forests was measured with a closed system. Loss rates ranged from 2.5 to 25 μgN m^{-2} day^{-1}. Laboratory tests suggest that rates could be low by a factor of two due to inefficiency of the ammonia absorbing devices used. Alteration of the microenvironment within the absorption chambers, especially exclusion of wind effects, may also have resulted in reduced NH_3-N volatilization from the soil, perhaps by another factor of two.

In the two grassland sites studied, ammonia volatilization was highest in spring, insignificant to medium-high in the summer, and low in winter. In the two forest sites, significant losses were measured only in spring and summer. Seasonal changes could be due to conditions affecting ammonia availability in the soil and conditions affecting its escape. Observation of fertilized plots—where ammoniacal N was not limiting—showed high potential loss rates in summer and low potential loss rates in winter, that were positively correlated with soil temperature and relatively correlated with soil water. The relatively low loss rates from grassland sites observed in the summer are therefore probably due to limited ammoniacal N availability.

Annual NH_3-N losses were estimated by averaging daily losses within each season and integrating over a whole year. NH_3-N losses for BOGR, AGSP, PSME, and ABLA sites were crudely estimated as 19, 26, 2.5, and 8 g ha^{-1} yr^{-1}, respectively. The differences may be due in part to differences in ammoniacal N availability, as were demonstrated in similar vegetation types by Weaver and Forcella (1979). Declines in temperature and pH and increases in water, organic matter, and cation exchange capacity as one moves up an altitudinal gradient from BOGR to ABLA are correlated with NH_3-N evolution and might explain corresponding declines in NH_3-N evolution. As such declines are marked under fertilized conditions where the amount of ammoniacal N is constant, differences in NH_3-N losses from unfertilized plots among habitat types are probably due to both availability of ammoniacal N and conditions affecting the volatilization process.

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APPENDIX

Table 6. Ammonia Volatilization From Unfertilized and Fertilized Plots.

Site[1]	Date	Unfert.	S.E.	Fert.	S.E.
		----------- μgN m^{-2} day^{-1} -----------			
BOGR	4-11 July 1982	2.4	1.4	2047. *	360.
	10-17 Aug. 1982	8.2*	2.4	1527. *	178.
	25 Aug.-1 Sept. 1982	6.3	4.7	2476. *	283.
	4-11 Oct. 1982	3.4*	0.4	2047. *	274.
	12-20 Nov. 1982	2.8*	1.5	698. *	198.
	11-18 Jan. 1983	4.8*	0.9	8.3*	2.5
	5-12 March 1983	3.2*	0.6	18.5*	6.3
	17-24 April 1983	6.7*	1.8	75.1*	38.0
	22-29 May 1983	15.7*	4.0	139.6*	66.4
AGSP	4-11 July 1982	2.6*	1.1	967. *	139.
	10-17 Aug. 1982	6.1*	2.0	788. *	76.3
	25 Aug.-1 Sept. 1982	0.4	0.4	1189. *	86.0
	4-11 Oct. 1982	12.2*	3.3	583. *	84.1
	12-20 Nov. 1982	1.5	0.8	67.2*	22.0
	11-18 Jan. 1983	4.5*	0.6	6.4*	2.2
	5-12 March 1983	2.5*	0.9	5.5*	1.8
	17-24 April 1983	8.3*	2.9	8.4*	2.6
	22-29 May 1983	24.6*	5.5	15.8*	6.5
PSME	4-11 July 1982	0.9	0.6	17.0*	5.1
	10-17 Aug. 1982	3.4	1.7	84.7*	10.2
	25 Aug.-1 Sept. 1982	8.7*	4.9	52.9*	11.4
	4-11 Oct. 1982	0.3	0.3	27.3*	6.1
	12-20 Nov. 1982	0.2	0.2	14.5*	3.5
	5-12 March 1983	0.3	0.2	1.3*	0.5
	17-24 April 1983	0.9	0.8	1.4	0.7
	22-29 May 1983	0.5	0.5	4.0*	1.2
ABLA	4-11 July 1982	2.8*	0.9	18.4*	5.8
	10-17 Aug. 1982	8.0*	3.2	87.3*	10.3
	25 Aug.-1 Sept. 1982	0.0	0.0	56.3*	13.9
	4-11 Oct. 1982	5.2*	2.4	13.3*	3.5
	12-20 Nov. 1982	0.3	0.2	13.0*	2.3
	11-18 Jan. 1983	1.4	0.8	2.2*	0.7
	5-12 March 1983	0.0	0.0	0.0	0.0
	17-24 April 1983	0.2	0.2	1.4*	0.4
	22-29 May 1983	4.8*	1.8	12.3*	6.5

*Denotes significance at the 0.10 level.

[1] Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

Table 7. Soil Temperature at 10 cm and Soil Water Potential at 10 cm and 25 cm During Sampling Periods.

Site[2]	Date	Max. Temp.	Min. Temp.	Average Temp.	Water Potential[1]	
					10 cm	25 cm
		C			bars	
BOGR	4-11 July 1982	–	–	20.0	0.3	0.3
	10-17 Aug. 1982	18.5	36.5	27.5	20.0	20.0
	25 Aug.-1 Sept. 1982	14.0	32.0	23.0	12.0	20.0
	4-11 Oct. 1982	0.0	13.0	6.5	0.5	2.9
	12-20 Nov. 1982	-3.0	-2.0	-2.5	1.3	1.1
	11-18 Jan. 1983	-8.0	-2.0	-5.0	20.0[3]	20.0[3]
	5-12 March 1983	-2.5	12.0	4.8	0.6	1.2
	17-24 April 1983	2.5	19.0	10.8	0.4	0.3
	22-29 May 1983	10.0	27.0	18.5	20.0	3.6
AGSP	4-11 July 1982	–	–	15.0	0.2	0.1
	10-17 Aug. 1982	17.5	36.5	27.0	20.0	20.0
	25 Aug.-1 Sept. 1982	13.5	31.5	22.5	19.0	20.0
	4-11 Oct. 1982	0.0	12.0	6.0	0.3	0.7
	12-20 Nov. 1982	-6.0	1.0	-2.5	0.8	1.2
	11-18 Jan. 1983	-4.0	-4.0	-4.0	20.0[3]	20.0[3]
	5-12 March 1983	4.0	8.0	6.0	0.3	0.4
	17-24 April 1983	12.0	16.0	14.0	0.3	0.3
	22-29 May 1983	11.0	25.0	18.0	1.2	0.4
PSME	4-11 July 1982	–	–	9.5	0.1	0.3
	10-17 Aug. 1982	9.0	20.0	14.5	0.6	0.2
	25 Aug.-1 Sept. 1982	9.5	13.0	11.3	0.3	0.0
	4-11 Oct. 1982	1.0	5.0	3.0	0.3	0.1
	12-20 Nov. 1982	-3.0	-2.0	-2.5	0.0	0.1
	5-12 March 1983	-3.0	-1.0	-2.0	0.8	0.3
	17-24 April 1983	-3.0	-1.0	-2.0	0.4	0.2
	22-29 May 1983	2.0	10.0	6.0	0.3	0.1
ABLA	4-11 July 1982	–	–	8.3	0.0	0.1
	10-17 Aug. 1982	10.0	15.0	12.5	0.6	0.4
	25 Aug.-1 Sept. 1982	9.0	14.0	11.5	0.4	0.3
	4-11 Oct. 1982	1.0	4.0	2.5	0.2	0.1
	12-20 Nov. 1982	-3.0	-2.0	-2.5	–[4]	–[4]
	11-18 Jan. 1983	-2.0	0.0	-1.0	0.0	0.4
	5-12 March 1983	-2.0	-2.0	-2.0	–[4]	–[4]
	17-24 April 1983	-1.0	-1.0	-1.0	–[4]	–[4]
	22-29 May 1983	1.0	10.0	5.5	0.2	0.7

[1] Water potentials given are the average of those observed at the beginning and end of the sampling period.

[2] Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

Table 7 (continued).

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[3] The soil at 10 cm and 25 cm was frozen; these values were therefore not included in the regressions, or presented in Figure 3.

[4] Gypsum blocks were inaccessible because of snow and ice.

Table 8. Maximum and Minimum Air Temperature and Snow During Sampling Periods at Weather Stations Near the Sampling Sites.*

Period		Max. T	Min. T	Snow Conditions
		-------°C-------		
Trident (BOGR)[1]				
4-11 July	1982	28.9	6.7	No data available
10-17 August	1982	35.0	7.2	
25 Aug.-1 Sept.	1982	32.2	5.6	
4-11 Oct.	1982	17.2	-3.3	
12-20 Nov.	1982	13.3	-17.7	
11-18 Jan.	1983	13,3	-11.7	
5-12 March	1983	21.1	-6.7	
17-24 April	1983	22.2	-1.7	
22-29 May	1983	31.1	3.9	
Belgrade AP (AGSP)				
4-11 July	1982	27.2	7.8	No snow
10-17 August	1982	35.0	6.1	No snow
25 Aug.-1 Sept.	1982	31.1	5.0	No snow
1-11 Oct.	1982	15.6	-5.0	Trace on 8 and 9
12-20 Nov.	1982	11.7	-18.9	Trace on 12, 13, 19 and 20
11-18 Jan.	1983	11.1	-12.8	No snow on ground
5-12 March	1983	20.0	-7.8	Snow 6 and 7
17-24 April	1983	20.6	-3.3	No snow
22-29 May	1983	28.3	-2.8	No snow
Bozeman 12NE (PSME and ABLA)				
4-11 July	1982	24.4	1.1	No snow
10-17 August	1982	28.3	0.6	No snow
25 Aug.-1 Sept.	1982	26.6	1.1	No snow
4-11 Oct.	1982	13.9	-10.0	Snowfall on 5, 7, 8, and 9
12-20 Nov.	1982	9.4	-21.1	150-300 mm of snow
11-18 Jan.	1983	12.2	-15.0	450 mm of snow on ground
5-12 March	1983	15.0	-13.3	> 500 mm of snow on ground
17-24 April	1983	16.7	-0.5	100-600 mm of snow on ground
22-29 May	1983	23.4	-1.7	No snow

*(USDC 1982-1983)

Max. T: Maximum temperature during the period.

Min. T: Minimum temperature during the period.

[1] Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

Table 9. Correlation Coefficients for the Relationship Between Soil Water and Soil Temperature at 10 cm for Each of the Four Sites.

Site	r
BOGR	-0.711
AGSP	-0.739
PSME	-0.009
ABLA	-0.739

Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

Table 10. Correlation Coefficients for the Relationship Between Soil Variables for Combined Data.

	Soil Temp at 10 cm	Season	Organic Matter	pH	CEC	Ca
	------------------------- r -------------------------					
Water potential at 10 cm	-0.700	-0.352	0.386	-0.433	0.398	-0.182
Soil temperature	1.000	0.747	-0.355	0.382	-0.351	0.099
Season		1.000	0.010	0.056	0.075	0.009
Organic matter			1.000	-0.855	0.649	-0.408
pH				1.000	-0.944	0.326
CEC					1.000	-0.170

Table 11. Incomplete Species Lists for the Study Sites.

Site	Species
BOGR	*Agropyron smithii* Rydb. *Agropyron spicatum* (Pursh) Scribn. & Smith *Allium textile* Nels. & Macbr. *Artemisia frigida* Willd. *Astragalus missouriensis* Nutt. *Bouteloua gracilis* (H.B.K.) Lag. *Bromus tectorum* L. *Carex filifolia* Nutt. *Cirsium* sp. *Gaura coccinea* (Nutt.) Pursh *Gutierrezia sarothrae* (Pursh) Britt & Rusby. *Liatris punctata* Hook. *Lomatium cous* (Wats.) Coult. & Rose *Opuntia polyacantha* Haw. *Oryzopsis hymenoides* (R. & S.) Ricker *Phlox hoodii* Rich. *Plantago patagonica* Jacq. *Poa sandbergii* Vasey *Sphaeralcea coccinea* (Pursh) Rydb. *Stipa comata* Trin. & Rupr. *Taraxacum officinale* Weber *Tragopogon aubius* Scop. *Viola nuttallii* Pursh
AGSP	*Achillea millefolium* L. *Agropyron smithii* Rydb. *Agropyron spicatum* (Pursh) Scribn. & Smith *Antennaria microphylla* Rydb. *Arenaria congesta* Nutt. *Arnica sororia* Greene *Artemisia frigida* Willd. *Bouteloua gracilis* (H.B.K.) Lag. *Bromus tectorum* L. *Carex stenophylla* Wahl. *Cirsium* sp. *Koeleria cristata* Pers. *Liatris punctata* Hook. *Lomatium* sp. *Lupinus sericeus* Pursh *Phlox hoodii* Rich. *Phlox longifolia* Nutt. *Poa pratensis* L. *Poa sandbergii* Vasey *Stipa comata* Trin. & Rupr. *Tragopogon dubius* Scop.

Table 11 (continued).

Site	Species
PSME	*Agoseris glauca* (Pursh) Raf.
	Achillea millefolium L.
	Berberis repens Lindl.
	Calamagrostis rubescens Buckl.
	Campanula rotundifolia L.
	Carex geyeri (Boott)
	Castilleia miniata Dougl.
	Chimaphila umbellata (L.) Bart.
	Clematis columbiana (Nutt.) T. & G.
	Cynoglossum officinale L.
	Fragaria virginiana Duchesner
	Galium boreale L.
	Hieracium umbellatum L.
	Iris missouriensis Nutt.
	Juniperus communis L.
	Juniperus scopulorum Sarg.
	Lupinus sericeus Pursh.
	Osmorhiza chilensis H. & A.
	Pinus contorta Dougl.
	Potentilla gracilis Dougl.
	Pseudotsuga menziesii (Mirbel) Franco
	Pyrola chlorantha Sw.
	Rosa woodsii Lindl.
	Spiraea betulifolia Pall.
	Symphoricarpos albus (L.) Blake
	Taraxacum officinale Weber
	Thalictrum venulosum Trel.
	Vaccinium membranaceum Dougl.
	Vicia americana Muhl.
ABLA	*Abies lasiocarpa* (Hook.) Nutt.
	Agoseris glauca (Pursh) Raf.
	Achillea millefolium L.
	Antennaria racemosa Hook.
	Arnica cordifolia Hook.
	Bromus inermis Leys.
	Calamagrostis rubescens Buckl.
	Campanula rotundifolia L.
	Carex geyeri Boott.
	Chimaphila umbellata (L.) Bart
	Elymus canadensis L.
	Fragaria virginiana Duchesner
	Galium boreale L.
	Geranium viscosissimum F. & M.
	Geum macrophyllum Willd.
	Goodyera oblongifolia L.
	Hieracium umbellatum L.

Table 11 (continued).

Site	Species
ABLA	*Linnaea borealis* L. *Osmorhiza chilensis* H. & A. *Phleum pratense* L. *Pinus contorta* Dougl. *Prunella vulgaris* L. *Pseudotsuga menziesii* (Mirbel) Franco *Pyrola chlorantha* Sw. *Rosa woodsii* Lindl. *Spirea betulifolia* Pall. *Symphoricarpus albus* (L.) Blake *Thalictrum venulosum* Trel. *Vaccinium membranaceum* Dougl. *Vaccinium scoparium* Leiberg *Veratrum californicum* Durand.

Sites were characterized by *Bouteloua gracilis* (BOGR), *Agropyron spicatum* (AGSP), *Pseudotsuga menziesii* (PSME), and *Abies lasiocarpa* (ABLA).

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