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USE OF FOREST ECOSYSTEM PROCESS MEASUREMENTS IN AN INTEGRATED ENVIRONMENTAL MONITORING PROGRAM IN THE WIND RIVER RANGE, WYOMING

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ABSTRACT

Three forest ecosystem processes—conifer needle retention, canopy litterfall, and litter decomposition—were measured as part of an integrated environmental monitoring program at a high-elevation site dominated by whitebark pine (Pinus albicaulis) *and Engelmann spruce* (Picea engelmannii). *Whitebark pine demonstrated much lower needle retention rates and slightly slower decomposition rates relative to Engelmann spruce. Studies to date reflect low productivity at this site and will provide baseline data against which future monitoring data may be compared.*

INTRODUCTION

This paper reports on forest ecosystem process measurements at an integrated environmental monitoring site located in a high-elevation, whitebark pine/Engelmann spruce (*Pinus albicaulis/Picea engelmannii*) system in the Wind River Mountains of western Wyoming. Ecosystem process measurements emphasized include conifer needle retention, canopy litterfall, and litter decomposition rates. Nutrient analyses were also conducted on conifer needles and litter samples. The primary objectives of this paper are: (1) to describe the rationale for applying these measurements to a monitoring program, (2) to summarize and discuss the data collected to date, and (3) to compare data with those collected at other remote sites.

This study represents an extension of previous monitoring and research conducted at other remote sites including national and international Biosphere Reserves and U.S. National Parks and wilderness areas (for example, Bruns and others 1982, 1984; Wiersma and others 1984; Wiersma and Otis 1986). In addition to the Wind River program, other sites that have been studied include Olympic National Park in Washington (Brown and Wiersma 1979), Noatak National Preserve and Biosphere Reserve in Alaska (Wiersma and others 1986), and Torres del Paine National Park in southern Chile (Bruns and Wiersma 1988a; Wiersma and others 1988). The basic objective of each of these monitoring programs is to provide the baseline data necessary to define the "natural" conditions at the site. This in turn allows better interpretation of the impacts of human activities on the system. A further goal of the Wind River monitoring program is to field test guidelines established by the U.S. Department of Agriculture, Forest Service, for monitoring the condition of remote, wilderness ecosystems (Fox and others 1987).

SYSTEMS APPROACH

An integrated, multimedia systems approach has been implemented in the Wind River monitoring program (Bruns and Wiersma 1988b). The design of the program is based on a watershed/drainage basin perspective (for example, Likens 1985; Minshall and others 1985), and links together key aspects of the forest, soil, stream, and lake components along selected pathways within the system (Bruns and Wiersma 1988b). This approach begins with the development of a simple conceptual design of the system to be monitored. This conceptual design is translated into a schematic diagram such as that shown in figure 1. Such diagrams are intended as heuristic tools for identifying system compartments of primary concern, delineating potential pollutant pathways through the system, and identifying potential critical pollutant receptors. This allows us to view the problem as one of pollutant sources and pathways to critical receptor components of the ecosystem. The ultimate goal of such a program is to identify a list of pollutant and ecosystem measurements capable of providing good, quality-assured data against which future observations may be compared, allowing us to assess the relative condition of the system.

The integrated ecosystem approach to environmental monitoring used in the Wind River monitoring program

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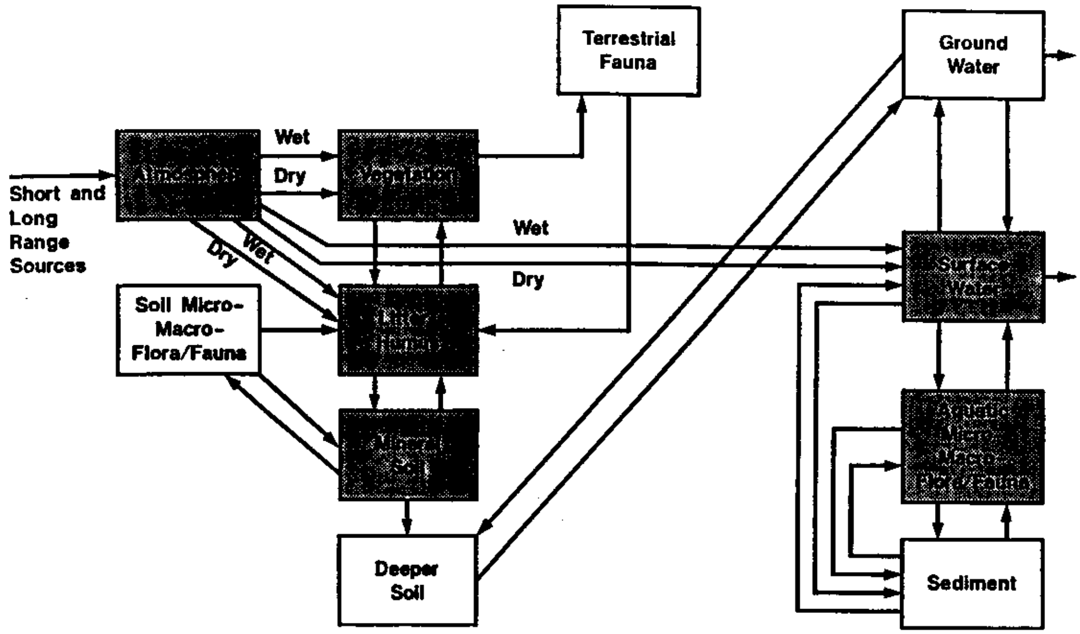

Figure 1—Conceptual approach to monitoring sensitive wilderness systems. Shaded compartments are included in the monitoring program.

involves the collection of two basic types of information: analyses of multimedia environmental samples, and measurement of terrestrial and aquatic ecosystem processes identified as potential indicators of pollutant impact to the system. Components examined in the monitoring program include the atmosphere, soils, aquatic chemistry, aquatic biology, salmonid fish, and vegetation. Specific methods and procedures used are provided elsewhere (Bruns and Wiersma 1988b; Bruns and others 1987, 1988; Fox and others 1987). The emphasis of this paper is on the portion of the program involving the measurement of forest ecosystem processes.

FOREST ECOSYSTEM PROCESSES

The measurement of parameters related to various ecosystem processes can be used to monitor changes in ecosystem condition (Baker and others 1986). To function adequately as an indicator of pollutant impact, an ecosystem parameter should satisfy the following criteria: (1) it should adequately reflect a process or function of the ecosystem, (2) it should respond to the input of an environmental pollutant in some predictable manner, (3) it should be measurable through time, (4) a small natural variability should be associated with it, and (5) the precision associated with the measurement of the parameter should be adequate to observe departures from the norm (Hinds 1984; McShane and others 1983). Needle retention, canopy litterfall, and litter decomposition rates were chosen because they appeared to meet these criteria, and because they had been established in previous investigations on ecosystem response to atmospheric pollutants.

Premature needle loss and the associated change in litterfall rate have been shown to be related to the input of air pollutants either due to the direct action of the pollutant on needle or leaf surfaces or due to damage to root systems caused by increased soil acidity (Mann and others 1980; Ulrich 1981; Williams 1980). Litter decomposition may also be affected due to heavy metal inputs (Coughtrey and others 1979; Strojan 1978), pH changes (Moloney and others 1983), or indirectly in response to changes in litterfall characteristics resulting in litter input containing higher nitrogen concentrations relative to lignin (Melillo and others 1982). The potential for disruption of nutrient cycles or primary productivity may therefore increase. Increases in tree mortality have also been associated with airborne pollution in North America and Europe (Freedman and Hutchison 1980).

The methodologies used to measure forest ecosystem processes in this program have been previously used in the Hoh Rain Forest of Olympic National Park (Baker and others 1986). Changes in needle retention, litterfall, and litter decay rates can result in changes in productivity and mortality. Observation of these processes allows the establishment of a broader basis on which to explain changes in the system. The range of natural variability in an ecosystem is an important consideration in the design of a monitoring program (Miller 1984). It may be difficult to distinguish between natural ecosystem variability and pollutant-induced change in the presence of extreme environmental conditions, short periods of pollutant exposure, or early stages of pollutant input. In such cases, the use of parameters with known and predictable fluctuations as indicators would aid in making that distinction.

A hypothetical response of needle retention, canopy litterfall, and tree mortality in response to the input of atmospheric pollutant is shown in figure 2. In response to pollutant input, conifer needle retention rates have been shown to decline significantly (Mann and others 1980; Williams 1980), typically with the youngest needles showing the greatest impact (Ulrich 1981). In response to the decrease in needle retention times, litterfall rates

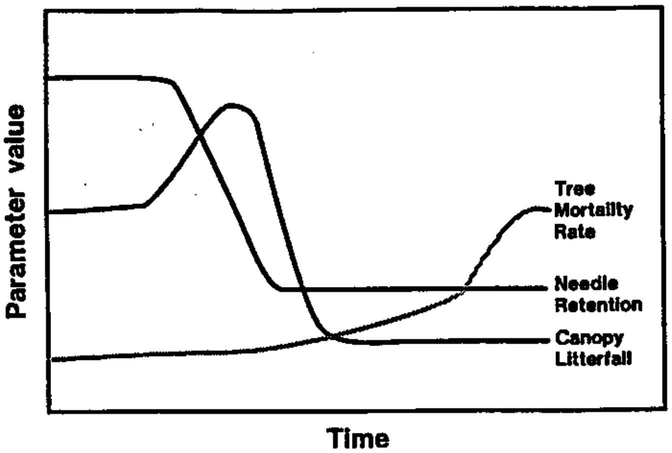

Figure 2—Hypothetical interactions between forest ecosystem parameters to input of atmospheric pollutants.

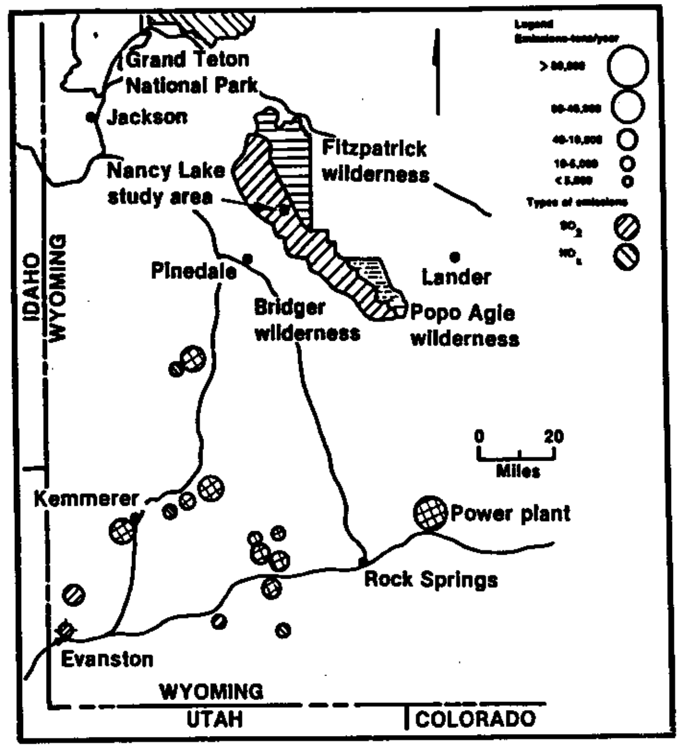

Figure 3—General location of the Wind River study site. Permitted point sources for SO_2 and NO_2 are also shown. Map based on USDA Forest Service (1984).

would be expected to increase initially, before decreasing and ultimately leveling off at a lower level. Similarly, the reduction in active photosynthetic area associated with decreased needle retention would be expected to contribute to the overall mortality rate of the stand, although other factors would undoubtedly impact the mortality rate as well.

Litter decomposition rate also plays an important role in nutrient recycling in forest ecosystems, and is influenced by many factors (Fogel and Cromack 1977). Alterations in nutrient release rates, therefore, may have an impact on tree growth and survival. Decomposition rate is not shown on figure 2, due to the difficulties associated with predicting the response of litter decomposition rates to the input of atmospheric pollutants. Pollutant input can have a detrimental effect on the organisms responsible for much of the decay, resulting in a decrease in the total rate of decay. The lignin-nitrogen ratio of the needles shed by the conifers may also play a significant role. If the response of the trees in the canopy is to prematurely shed younger needles, the lower lignin/nitrogen ratios typically associated with younger foliage may contribute to an increase in the decay rate of the litter (Melillo and others 1982).

The intent of the model proposed in figure 2 is to integrate ecosystem response to atmospherically deposited pollutants in remote areas. The long-term goal of this study is to test these and other hypotheses against future changes in pollutant levels.

STUDY SITE

The study site is located at Nancy Lake, in the upper portion of the Hobbs Lake watershed within the Bridger Wilderness Area of the Bridger-Teton National Forest, WY (fig. 3). Nancy Lake is located at an elevation of 3,140 m (10,400 ft), and is approximately 2 ha (5 acres) in surface area. Soils at the study area are thin, and the area is sparsely forested with Engelmann spruce and whitebark pine, interspersed with small numbers of subalpine fir (*Abies lasiocarpa*). Some environmental monitoring previously had been conducted by the Forest Service in the area (USDA FS 1984). The study site was originally chosen because of the presumed sensitivity of high-mountain ecosystems to atmospheric pollutants, the presence of other ongoing complementary monitoring projects, relatively easy access to the site, and potential for the area to receive measurable pollutant input from energy development activities upwind (fig. 3). As such, the Wind River Mountains provide an ideal location for an integrated monitoring project (Wiersma and others 1985).

METHODS

Permanent Reference Stands

Two permanent 0.25-ha (0.6-acre) study plots were established within different forest patches during the 1987 field season. The plots are referred to as BR-1 and BR-2, and were chosen to reflect the basic forest types found in the Nancy Lake area. These forest types fit into the habitat types described by Steele and others (1983); BR-1 represents the *P. engelmannii/Vaccinium scoparium* type and BR-2 represents the *P. albicaulis* phase of the *A. lasiocarpa* type. Plot boundaries were surveyed with compass and meter tapes. Diameters of all trees greater than 1-cm diameter at breast height (d.b.h.) were measured, and these trees were tagged.

Conifer Needle Retention

Branches were selected for use in determining needle retention from whitebark pine and Engelmann spruce, the two dominant tree species found in the area. Single branches were sampled from five trees of each species, for each stand. Each branch was placed in a plastic bag, labeled, and was returned to the laboratory for counting. All were placed in a refrigerated room within 36 hours of collection, and were counted within 4 days of collection. Subsamples of needles from the branches sampled were analyzed for nutrient concentrations.

In the laboratory, three secondary branches were selected from each primary branch for needle retention counts. The secondary branches were divided into single-year growth increments, starting with the most recent growth and proceeding through the oldest segment for which needles were still present. Because the spruces were found to retain their needles for up to 30 years, only the first 5 years and two randomly selected, older needle age classes were sampled for each branch. This reduced the time required to count the needles while still providing an estimation of needle loss over the longer time frame. For each age class counted, measurements were made of twig length, number of needles present, and the number of needles absent as determined by the presence of residual needle scars. The fraction of needles remaining on the segment was then calculated for each segment by dividing needle number by the sum of the needle number and the number of residual needle scars. In the case of whitebark pine, fascicles and fascicle scars were counted.

Canopy Litterfall

The method used to determine litterfall rates was modified from Baker and others (1986). Twelve pairs of litter collection buckets were placed in each reference stand. The area of an individual bucket was 0.066 m^2 (0.72 ft^2). Material falling into the buckets was collected in nylon mesh liners. Three bucket pairs were placed randomly in each of four quadrants within each stand. One bucket pair in each trio was "fixed"; it always remained in the same location. The other two pairs were randomly relocated within the quadrant at the beginning of each sampling period. This fixed and movable bucket system allowed for the determination of both spatial and temporal variability of litterfall while minimizing the total number of buckets required (Reiley and others 1969). Bucket pairs were used to provide samples for the determination of both nitrogen/lignin ratio and trace element analysis (Baker and others 1986).

Litter bucket samples were collected three times each during the 1987 and 1988 field seasons. Samples were returned to the laboratory for processing. The samples were dried at 50 °C for 48 hours and weighed. Major components (needles, cones, fine branches) were separated. Each category was weighed separately and pooled for the season. These samples were analyzed for lignin and nitrogen concentration by methods described by Goering and Van Soest (1970) and Isaac and Johnson (1976), respectively.

Litter Decay Rates

Annual decay rates were determined for various species using litter bags (Crossley and Hoglund 1962; Singh and Gupta 1977). Litter from species indigenous to this study area was collected for this portion of the study just prior to abscission. These species included whitebark pine, Engelmann spruce, subalpine fir, and willow (*Salix* spp.). Leaves from Pacific dogwood (*Cornus nuttallii*) and needles from western white pine (*Pinus monticola*) were also used. These additional species were collected in Oregon, and were selected to provide a wider range of lignin and nitrogen concentrations.

Litter was weighed and placed in 20- by 20-cm polyester bags of 1-mm mesh size. Each bag contained approximately 10 g (dry weight) of litter. Subsamples of each species were used to determine moisture, lignin, and nitrogen content. The litter bags were placed in the field in August 1987 and were collected in August 1988. After collection, the remaining litter was removed from each bag, ovendried, and weighed. Litter loss was expressed as a rate constant (k), as well as a percentage (Jenny and others 1949; Olson 1963).

Elemental Analyses

In association with the 1987 needle retention study, needle samples were collected for elemental analysis from whitebark pine, Engelmann spruce, and subalpine fir. Litterfall samples collected during the 1987 and 1988 field seasons were also analyzed to determine concentrations of various elements. Litter bucket samples collected in June 1988, representing the overwinter accumulation of litter, were not used for elemental analysis due to the uncertainties associated with the effects of snowpack and other factors on the litter. Elemental analyses were performed by spark source emission spectroscopy (Alexander and McAnulty 1981).

RESULTS

Needle Retention

The results of the 1987 needle retention study are shown in figure 4. Data from both stands are combined because no significant difference was found between stands. Eighty percent of the whitebark pine needles observed were lost over a 12-year period. In contrast, Engelmann spruce retained over 75 percent of its needles during the same time frame, and did not reach the 50 percent loss level until the 14th year.

Chemical analysis indicated that both species had their highest nitrogen content in the needles of the current year (table 1). The nitrogen content of spruce needles was initially higher than that of the pine, but this difference decreased as needle age increased. All needle age classes of whitebark pine contained higher lignin content than corresponding age classes from Engelmann spruce.

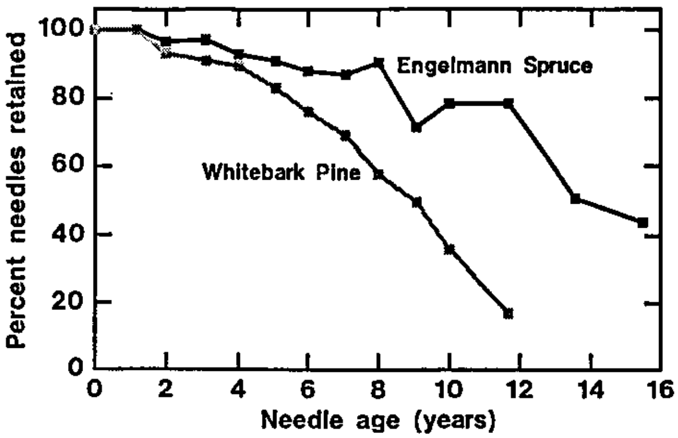

Figure 4—Needle retention for whitebark pine and Engelmann spruce, Nancy Lake, WY, 1987.

Canopy Litterfall

The 1987 and 1988 litterfall data for the two permanent stands are shown in table 2. These data indicate that the litterfall rates during 1988 were substantially higher than those of 1987. In both years, the total litterfall rate for BR-2 exceeded that of BR-1. In both stands, the dominant component of the litterfall was conifer needles.

Litter Decay

The initial nitrogen content of litter used ranged from 0.61 percent for whitebark pine to 1.18 percent for willow. Lignin is highest in the two pine species, and is lowest in the dogwood (table 3). Litter decomposition rate constants (k) were determined for each species by dividing the natural logarithm of the fraction of litter remaining by the time the litter remained in the field (years), and are shown in table 4. Of the species used in the study, decomposition of Pacific dogwood was the most rapid; the decomposition rate was slowest for western white pine.

Analysis of variance for the litter decay rates indicates that there were highly significant differences in decay rates between species, but not between stands (BR-1 and BR-2). The regression between the annual decay rate constants (k) determined for the six species used in this experiment and their respective lignin/nitrogen ratios was highly significant ($p < 0.001$):

$$k = 1.453(\text{lignin/nitrogen})^{-0.564}$$
$$r^2 = 0.93$$

The relationship between the decay constants and the lignin/nitrogen ratio of the species used for the Nancy Lake study site is shown in figure 5.

Table 1—Lignin and nitrogen content of conifer needles of seven different age classes, Nancy Lake, WY, 1987

	Whitebark pine		Engelmann spruce	
Needle age	**N**	**Lignin**	**N**	**Lignin**
Year	*Percent*			
<1	1.93	13	2.08	5
1	1.21	16	.74	10
2	1.30	17	.66	9
3	1.21	19	.66	9
6	1.06	12	.65	9
10	.84	14	.63	8
13	.92	13	(1)	(1)

1Insufficient sample volume for analysis.

Table 2—Litterfall data, Nancy Lake study site, 1987-1988

Collection date	Days in field	Total litter mass g/m²		Seasonal litterfall rate g/ha day	
		BR-1	**BR-2**	**BR-1**	**BR-2**
08/12/87	32	7.2	7.4		
09/16/87	35	3.5	10.7		
10/06/87	20	2.6	9.3		
Seasonal Total	87	13.3	27.4	1,500	3,150
07/18/88	19	13.9	12.4		
08/30/88	43	8.4	16.3		
Seasonal Total	62	22.3	28.7	3,600	4,630

Table 3—Initial lignin and nitrogen content of litter used in the determination of decay rates percent

	Lignin		Nitrogen		Lignin/N
Species	**Mean**	**Stan. dev.**	**Mean**	**Stan. dev.**	**ratio**
Pacific dogwood	6.2	0.20	0.87	0.20	7.1
Willow	21.4	1.51	1.18	.07	18.0
Engelmann spruce	13.4	.15	.74	.03	18.0
Subalpine fir	20.5	.70	.77	.05	26.0
Whitebark pine	23.4	2.02	.61	.02	38.0
Western white pine	27.0	3.48	.37	.01	73.0

Table 4—Decay constants for litter of six tree and shrub species, Nancy Lake, WY, 1988 (per year)

	Stand BR-1		Stand BR-2	
Species	**Mean**	**Stan. dev.**	**Mean**	**Stan. dev.**
Pacific dogwood	0.487	0.186	0.471	0.029
Willow	.284	.047	.266	.019
Engelmann spruce	.262	.038	.255	.020
Subalpine fir	.220	.023	.276	.035
Whitebark pine	.202	.032	.228	.047
Western white pine	.111	.019	.121	.019

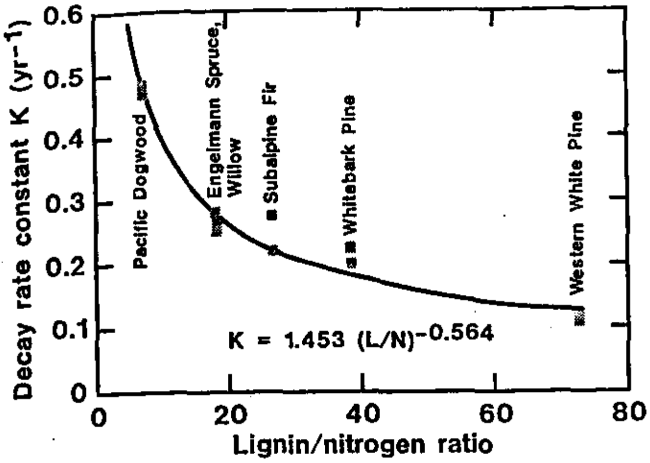

Figure 5—Relationship between decay rate constant and lignin/nitrogen ratio for six species, Nancy Lake, WY, 1987-88.

Elemental Analyses

Results of the analyses of litterfall samples and conifer needles for selected nutrients (P, K, Ca, and Mg) are shown in table 5.

DISCUSSION

The data collected during the 1987 and 1988 field seasons provide an indication of the recent status of these ecosystem processes at the Nancy Lake study site. Future measurements of these parameters can be compared with these baseline values to observe changes in the system. Additional data sets are required before we can adequately determine whether needle retention, canopy litterfall, and litter decomposition meet the five criteria described above for use as indicators of pollutant input.

Needle Retention

Needles of both whitebark pine and Engelmann spruce are retained for longer periods of time at this high-elevation system than are those of conifers observed in more temperate forests of the Pacific Northwest (Baker and others 1986). Many of the spruce examined at the Nancy Lake site retained needles for up to 30 years; this represents extremely long retention times for spruce needles (Harlow and Harrar 1958). We hypothesize that this extended retention rate represents a response to the shorter growing seasons or poor soil development characteristic of these high-elevation sites, where branch elongation and growth of new photosynthetic tissue are restricted Preliminary data from a study designed to examine the relationship between needle retention rate and elevation in the Nancy Lake area seem to support the hypothesis (White and Wiersma, in preparation). The trees in the Nancy Lake area appear to have responded to the environmental conditions of the site by maintaining their needles for longer time periods. The older needles presen do show signs of age or exposure to the harsh environmental stresses naturally present at the site (Bruns and others 1988).

Canopy Litterfall

Canopy litter input is a more difficult parameter to assess due to the limited collection period and to the prol lems associated with collecting accurate data during the winter months. These problems included damage to the collection buckets from snowpack and animals. The severe drought conditions prevalent in the area during 19ξ may have resulted in annual litter input rates that were abnormally high for this area. Additional data are neces sary to determine the extent of the natural variability associated with this parameter. The annual input rates determined for the two stands are extremely low compared with those of more temperate forest sites in the

Table 5—Concentrations of selected nutrients in conifer needles and litter samples, Nancy Lake, WY, 1987-1988 (all values in parts per million)

	Litterfall samples				
Collection date	Stand	P	K	CA	MG
August 1987	BR-1	2,800	2,830	4,790	972
	BR-2	2,460	2,410	2,990	1,330
September 1987	BR-1	1,530	2,900	5,160	835
	BR-2	1,270	1,680	3,450	1,330
October 1987	BR-1	1,160	2,120	5,920	769
	BR-2	989	1,690	6,280	1,110
July 1988	BR-1	2,560	2,440	7,200	961
	BR-2	1,600	1,970	6,180	1,260
August 1988	BR-1	1,890	2,250	11,800	685
	BR-2	1,450	1,750	8,365	1,220
	Conifer needles				
Collection date	Species	P	K	CA	MG
July 1987	Whitebark pine	1,710	2,180	7,600	1,420
July 1987	Engelmann spruce	1,240	2,580	15,400	767
July 1987	Subalpine fir	1,460	2,060	15,400	766

Pacific Northwest (Baker and others, in preparation; McShane and others 1983). This reflects the relatively low productivity expected in a forest with a limited growing season. The difference in litterfall rates found between the two stands can primarily be attributed to the presence of the many small firs in the understory of BR-2. Other possible contributing factors include differences in relative canopy cover, basal area factor, and the number of stems per acre between the two stands.

Litter Decomposition

Decomposition rates have been shown to be dependent on the initial ratio of the concentrations of lignin and nitrogen in the litter, with litter containing high relative concentrations of lignin expected to exhibit the slowest decomposition rates (Melillo and others 1982). This relationship was observed in the Nancy Lake decomposition data shown in figure 5. Decay rates, however, are also a function of climatic factors. The relationship between decay rates and lignin/nitrogen ratios from Nancy Lake is compared with those of other sites in figure 6. These sites represent a wide variety of climatic conditions, and include sites in Washington State (Harmon and others, in press), North Carolina (Cromack and Monk 1975), and Puerto Rico (La Caro and Rudd 1985). At any given lignin/nitrogen ratio, the decay rate constant is less at the Nancy Lake site than at other sites. This phenomenon appears to be due to a more harsh climate characteristic of the Wind River range.

Elemental Analyses

A cursory review of the nutrient concentration data from conifer needles and litter samples indicates that the levels of these nutrients in litter are similar in both stands (table 4). With respect to the needles, it is interesting that whitebark pine needles were found to have only about half the calcium content of either Engelmann spruce or subalpine fir while possessing almost twice the concentration of magnesium. Comparison of the differences in calcium content of green needles versus that of litter collected during the same time frame (August 1987), indicates that a significant reabsorption of calcium from needles prior to abscission may be occurring. A more detailed review of the nutrient concentration data will be provided along with that of other chemical elements in these and other environmental media in a future report (Wiersma and others in preparation).

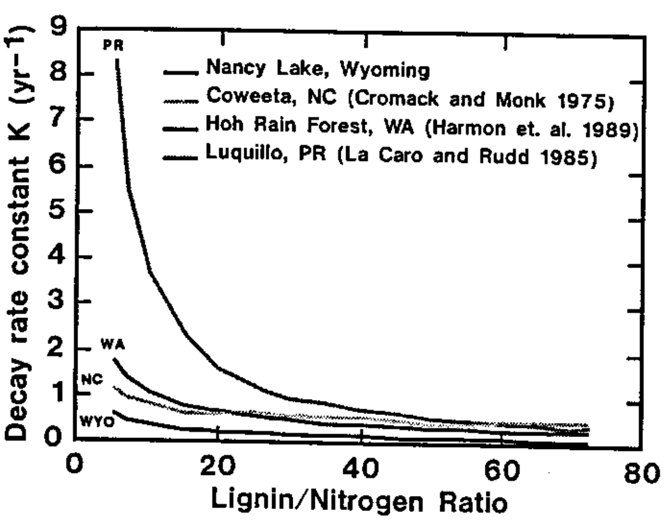

Figure 6—Comparison of relationship between decay rate constant and lignin/nitrogen ratio for sites of varying climatic conditions.

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