韓國林學會誌 85(4) : 656-666. 1996
Jour. Korean For. Soc. 85(4) : 656-666. 1996

Changes in Nutrient Distribution, Cycling, and Availability in Aspen Stands after an Intensive Harvesting[1]

Dong Yeob Kim[2]

集約的인 伐採로 인한 美國사시나무림내 養分의 分布, 循環 및 可溶性의 變化[1]

金 東 燁[2]

ABSTRACT

Aspen demand has increased recently in the Great Lakes region in the United States. Since aspen has moved into the region in late 1800's, its growing stock has increased so as to change forestry industry of the Lake States. Intensive timber harvesting and biomass removal may cause nutrient depletion, especially on nutrient-poor sites. Forest nutrients and nutrient cycling were investigated in aspen stands of 7-10, 27-33, and 41-42 year-old growing on sandy soils in Minnesota. Nutrients added to the aspen stands by atmospheric deposition and soil weathering were efficiently absorbed and stored in the tree biomass. Aboveground biomass increased from 24.4 $t \cdot ha^{-1}$ at young stands to 139.2 $t \cdot ha^{-1}$ at mature stands. Nutrients accumulated in the tree biomass showed same magnitude of difference. Nutrients added to the site through atmospheric deposition were in the order of Ca, N, K, Mg, and P. Annual litterfall was greater in older stands. However, the amount of nutrients returned by litterfall was not significantly different among stand ages due to the greater nutrient contents in the litterfall of young stands. Litter decomposition and nutrient release rates were greater at young stands than at older stands. Likewise, nutrient availability was higher in young aspen stands and became lower as the stands grew older. Nutrient leaching loss was minimal at all stand ages. Soil N mineralization was greater at young stands than at older stands. Nutrient cycling process was facilitated in young aspen stands with an increased level of available nutrients. Based on the estimations of nutrient balance and nutrient removal by harvesting, Ca was the most critical element which was likely to be depleted if aspen stands are intensively harvested with short rotations.

Key words : Populus tremuloides, *nutrient cycling, available nutrients, tree biomass, soil nutrients, atmospheric deposition, leaching*

요 약

미국 오대호 지역에서는 최근 들어 미국사시나무의 수요가 증가하고 있다. 미국사시나무는 1800년도 후반부터 이 지방에 들어오기 시작하면서 축적이 계속 증가해 지금은 오대호 지방의 임업 관련 산업의 구조를 바꾸기에 이르렀다. 집약적인 임목 벌채와 임지로부터 목재 반출은 양분의 손실을 초래해 양분 부족으로 인한 생산력 저하를 일으킬 수 있다. 산림내 양분과 양분순환의 변화 과정을 미국 미네소타의 사질토양에서 자라는 7-10, 27-33, 41-42년생 미국사시나무림에서 조사하였다. 대기로부

[1] 접수 1996년 8월 23일 Received on August 23, 1996.
[2] 성균관대학교 조경학과 Department of Landscape Architecture, Sung Kyun Kwan University, Suwon, Korea.

터 그리고 풍화에 의해 유입되는 양분은 식물체내에 효과적으로 흡수, 저장되었다. 지상부 생물량은 유령림에서 24.4 t·ha^{-1}였고 성숙림에서 139.2 t·ha^{-1}로 증가하였으며, 여기에 저장된 양분의 총량도 같은 비율로 증가 하였다. 대기로부터 유입되는 양분의 양은 Ca, N, K, Mg, P 순으로 많았다. 연간 총낙엽생산량은 성숙림으로 갈수록 많았다. 그러나 유령임에서는 낙엽내 양분 함량이 높아 낙엽으로 인해 임지에 환원되는 양분의 총량에는 큰 차이가 없었다. 낙엽 분해와 양분 방출률은 성숙림보다는 유령림에서 높았고, 따라서 가용성 양분도 유령림에서 가장 많았다. 용탈에 의한 양분 손실은 모든 조사구에서 극히 적은 것으로 나타났다. 질소무기화작용은 유령림에서 가장 높았고 지하수위가 높은 곳에서는 2-3배 더 상승하였다. 양분순환 과정은 가용 양분의 증가와 함께 유령림에서 촉진된 것을 알 수 있었다. 양분의 수지균형과 벌채에 의한 양분 손실량을 고려했을 때 짧은 벌기령에 집약적인 벌채가 계속 될 경우 칼슘이 가장 고갈되기 쉬운 양분인 것으로 나타났다.

INTRODUCTION

Aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) is one of the principal timber resources in the Lake States of the United Utates. Aspen fiber production has increased in this region and is expected to increase over the next few decades. Hardwoods constitute 76 percent of the total pulpwood(8.1 million cords) harvested in this region in 1988 and nearly 60 percent of the hardwood production was aspen (Hackett and Smith, 1990). The need to meet these increased demands forced forest land to be managed more intensively. Forest productivity has been increased by whole-tree harvesting and short rotations. Whole-tree harvesting method increased biomass yields as much as 300 percent compared to the conventional harvesting(Keays and Hatton, 1975). This increase in harvest intensity also increased nutrient removal from the site by 2 to 5 times(Malkonen, 1976). Aspen is generally very effective in nutrient uptake and accumulating them in wood and bark tissues.

Increasing trends of aspen harvesting brought a concern of nutrient depletion from the forest ecosystem, especially for Ca and Mg. Researchers revealed potential Mg and Ca depletion in aspen forests after a series of harvesting(Boyle and Ek, 1972; Boyle et al., 1973; Silkworth and Grigal, 1982). Calcium depletion was also likely in other forests in eastern U.S.(Federer et al., 1989). Although there are potentials for Ca and Mg depletion by intensive harvesting, they may not come immediately after the harvesting because of the initial abundance of the nutrients in the soil. Aspen timber harvesting, whole-tree or otherwise, in the upper Great Lakes did not have any measurable impact on forest floor, soil organic matter, and soil nutrients(Alban and Perala, 1990a). Logging slash of aspen contains up to three to four times more nutrients than in annual litterfall, and those nutrients are added to the site when litterfall nutrient return is significantly reduced by harvestingL(Alban and Perala, 1990b). Continuation of whole-tree harvesting may cause a degradation of site productivity by nutrient loss from the site and/or by changing soil conditions.

Many nutrient balance studies provided valuable information of harvesting effects on site nutrient capital. However, they may be insensitive to change in nutrient availability. In aspen forests, plant Ca uptake exceeds Ca addition to the soil (Alban, 1982). This results in Ca redistribution from mineral soil to forest floor and reduction of exchangeable Ca pools in the soil. Decomposition rate of O horizon determines Ca availability in the soil. Calcium oxalate, which facilitates soil weathering, may also play an important role in maintaining the availability of Ca and other nutrients in aspen forests.

Although nutrients can be added by forest fertilization in some situations, management of nutrient reserves and its availability is an important aspect of forest management. It is difficult to evaluate the impact of nutrient loss induced by timber harvesting on future site productivity. It requires information on nutrient requirements of trees, nutrient availability in the soil, and tree growth responds to environmental and nutritional changes on a long-term basis. The objective of this study was to investigate the changes in nutrient distribution, cycling, and availability in aspen forests as an initial approach to assess the impacts of intensive timber harvesting on site productivity.

MATERIALS AND METHODS

Site description

The study site was located at Cloquet Forestry Center of University of Minnesota in Carlton County, Minnesota, U.S.A. Cloquet Forestry Center is located on Cloquet outwash plain, at an elevation of 380 to 400m, formed during the Split Rock phase of the Superior lobe. Research plots were established exclusively on Omega soil series(mixed, frigid, Spodic Udipsamments). The soil was sandy and nutrient poor and was considered to exert timber harvesting effect on forest nutrients better than other soils.

Forest cover of the Cloquet Forestry Center area was divided into three different types; red pine (*Pinus reginosa* Aiton), white pine(*P. strobus* L.), and jack pine(*P. banKsiana* Lamb.); spruce-fir; and aspen-birch. One-third of this area was predominantly covered with low-land forest species, black spruce(*Picea mariana*(Mill.) B.S.P.), tamarack(*Larix laricina*(Du Roi) K. Koch), and northern white cedar(*Thuja occidentalis* L.). Research plots were established on the stands where aspen consisted over 60 percent in species composition (Table 1). Understory species in the plot was primarily beaked hazel(*Corylus cornuta* Marsh.), mixed with red maple(*Acer rubrum* L.) and bush honeysuckle(*Diervilla lonicera* Mill.) in some plots. Herbaceous ground cover was mainly aster (*Aster* sp.), clintonia(*Clintonia borealis*(Ait.) Raf.), wild sarsaparilla(*Aralia nudicaulis* L.), eastern bracken fern(*Pteridium aquilinum*(L.) Kuhn.), and sedges(*Carex* sp.).

The area has a continental climate with long and cold winters, warm summers, and precipitation uniformly distributed throughout the year. Average monthly temperature ranged from -9.3℃ in December to 16.2℃ in July 1992. Annual precipitation was 693mm in 1992.

Data collection

The research plots were established with completely random design on aspen stands of three age groups(young, 7-10 yrs; mid-age, 27-33 yrs; and mature, 41-42 yrs). Each age group had two stands and two more stands with high water table were added to the young age group. One 100m×100m square plot was established in each stand. Each plot was divided into four 50m×50 m subplots and a 0.05 ha circular vegetation plot was established in each subplot. Two circular shrub plots of 4m^2 were included in each vegetation plot. A 1m×0.5m herbaceous ground cover plot was established in each shrub plot.

Precipitation was collected from Cloquet Forestry Center with a polyethylene funnel. Collected samples were analyzed for inorganic nitrogen(N) using Wescan Ammonia analyzer and for Kjeldahl N using block digester and Technicon Autoanalyzer. Other nutrients were analyzed by Research Analytical Laboratory, Department of Soil Science, University of Minnesota with an inductively coupled plasma spectrometer(ICP)(EPA, 1971). The bulk precipitation samples were assumed to ac-

Table 1. Stand and soil characteristics of study sites.

Plot	Stand age	Tree no.	Average dbh	Basal area	Site index	Soil texture		Bulk density		Soil pH	
	yr	#/h	cm	m^2/ha	m(50)	A	B	A	B	A	B
Mature	41	740	16.1	31.6	24	SL	LS	0.69	1.29	4.8	5.2
	42	1055	14.1	27.7	21	SL	LS	1.22	1.30	4.9	5.7
Mid-age	33	1295	11.6	21.2	23	SL	LS	1.02	1.21	5.3	5.5
	27	2705	8.5	21.5	23	SL	LS	0.96	1.40	5.8	5.6
Young	10	8694	4.4	8.5	21	SL	LS	0.97	1.30	5.5	5.9
	7	4990	3.8	4.1	18	SL	SL	1.26	1.49	5.9	5.4
Young (wet)	10	7574	5.2	9.8	21	SL	LS	1.36	1.41	5.9	5.6
	8	9754	4.1	8.4	21	SL	SL	1.37	1.41	5.1	5.3

count mostly for wet deposition. Dry deposition was estimated from wet to dry deposition ratios of N 1 : 1, P 1 : 1, K 1 : 1.567, Ca 1 : 1.295, and Mg 1 : 0.77, which were obtained from the low elevation forests in the United States(Johnson and Lindberg, 1992).

Vegetation was stratified into three layers; tree layer, diameter at breast height(dbh) 2.5cm and over; shrub layer, dbh less than 2.5cm; and herbaceous ground cover. Tree biomass was estimated using dbh and biomass equations developed by Perala and Alban(1993). Shrub base diameter at 15cm aboveground was measured in August 1991. The base diameter was used to estimate shrub biomass using biomass equations developed by Perala and Alban(1993). Herb, plant leaf and woody tissue samples were collected during the summer of 1991 and analyzed for nutrients with ICP.

Litterfall was collected, using four 1m×1m litter traps in each plot, biweekly in fall and bimonthly during other seasons in 1992. O horizon biomass samples were also collected from four locations in each plot. All litter samples were analyzed for nutrients with ICP. Leaf litter bags were made of fiberglass net with a mesh size of 1mm, and were buried in O horizon. After 6, 9, 12, and 18 months, litterbags were collected and analyzed for organic carbon and other nutrients with ICP.

Soil samples were collected from each horizons and analyzed for chemical properties including organic carbon, total Kjeldahl N, total P, and basic cations. Soil N mineralization was measured by *in situ* incubation method with PVC tube (Raison et al., 1987; Adams and Attiwill, 1986; Rapp et al., 1979). The intact soil cores were incubated aerobically at monthly interval over a 6 month period from May to November 1992. After the incubation, upper 15cm soil was collected and analyzed for mineral N with a Wescan ammonia analyzer. Nitrogen mineralization was determined from the difference of N level between the start to the end of the incubation. Denitrification activity was measured with intact soil cores in PVC tube. Soil cores were measured for denitrification by an acetylene bocks method at 3-week intervals over a 6 month period from May to October 1992(Burton and Beauchamp, 1984; Myrold, 1988; Robertson and Tiedje, 1984). Sample gas was analyzed for N_2O using Shimadzu GC-14A gas chromatograph equipped with a ^{63}Ni electron capture detector operated at 150℃. Argon -methane(95 : 5) was used for carrier and backflush gas. Nitrogen availability index was measured using anaerobic incubation of soil(Keeney, 1982). The incubated soil-water mixture was analyzed for ammonium content using a Wescan ammonia analyzer.

Soil solution was collected from ceramic-cup lysimeters during May to October 1992(Hansen and Harris, 1975; Shephard and Mitchell, 1991; Wagner, 1962). The collected soil solution samples were analyzed for nutrients by ICP. To determine nutrient outputs, the nutrient concentrations were coupled with the estimates of soil water flux. Soil water flux can be estimated from water balance:

$$P=R+L+S+ET \quad (1)$$

where P is precipitation, R is surface runoff, L is leaching, S is change in soil storage, and ET is evapotranspiration. Assuming that surface runoff is negligible and change in storage approaches zero as time interval increases, the amount of water leached from the system was obtained by following equation:

$$L=P-ET \quad (2)$$

Evapotranspiration was estimated from monthly precipitation and mean monthly temperature (Black, 1966; Thornthwaite and Mather, 1957).

RESULTS AND DISCUSSION

Nutrient distribution

Total organic matter(OM) increased in the vegetation of aspen stands about 4 times from 10 years to 40 years of stand age(Table 2). Shrubs and herbs contributed approximately 2 percent of the vegetation OM. The amount of soil OM including forest floor OM remained at the same

Table 2. Organic matter(t ha^{-1}) and nutrients(kg ha^{-1}) in vegetation and soil in aspen stands at three different ages.

	Foliage	Branch	Bark	Wood	Root[1]	Herb	Total	Soil			System total
								O	A	B[2]	
Organic Matter											
Mature	5.2	18.7	23.0	95.6	27.8	0.5	170.8	19.4	30.9	32.4	253.5
Mid-age	3.4	9.6	13.3	60.2	17.4	0.7	104.6	18.7	30.0	29.0	182.3
Young	2.0	1.4	4.3	19.6	12.4	0.5	40.3	19.4	34.4	35.4	129.5
Total N											
Mature	123.1	180.0	76.6	112.6	97.4	9.5	599.1	255.6	880.8	1150.7	2886.3
Mid-age	73.9	89.7	45.4	77.4	62.5	12.3	361.1	222.4	1029.2	1115.9	2728.7
Young	42.8	12.0	34.7	31.3	44.8	10.0	175.5	377.7	1449.2	1093.6	3096.0
Total P											
Mature	9.3	28.8	10.6	19.0	25.1	1.4	94.2	24.1	288.0	1495.2	1901.5
Mid-age	6.2	13.2	7.4	14.9	15.6	1.9	59.2	25.4	370.9	1884.1	2339.6
Young	4.1	1.6	4.7	4.9	11.2	1.6	28.2	29.1	504.5	1822.8	2384.5
K											
Mature	38.6	84.1	59.8	125.1	105.8	15.2	428.7	45.1	3424.0	5313.9	9211.7
Mid-age	25.7	42.7	46.1	72.5	67.7	18.7	273.3	52.2	2958.0	8910.8	12194.2
Young	19.0	6.0	26.2	18.6	48.5	17.2	135.4	44.4	1197.4	5977.7	7354.8
Ca											
Mature	57.2	233.8	317.3	137.1	261.7	5.3	1012.4	367.0	3040.0	8228.7	12648.2
Mid-age	40.6	124.2	168.1	123.2	217.1	5.3	678.5	368.1	2464.6	13762.1	17273.2
Young	16.4	16.1	73.4	40.5	155.6	5.4	307.3	359.0	3671.9	10785.8	15123.9
Mg											
Mature	12.7	25.9	16.4	18.5	27.8	1.5	102.8	40.8	1134.4	12547.3	13825.3
Mid-age	7.8	11.1	10.3	13.0	19.1	1.6	62.8	36.9	1860.8	15933.2	17893.7
Young	4.7	1.5	5.7	5.5	13.7	1.4	32.5	38.3	1370.8	13030.4	14471.9

[1] Root biomass and nutrients from Ruark and Bockheim (1987) and Pastor and Bockheim(1984).
[2] B horizon soil to the depth of 50cm.

level at all stand ages, but the soil/system OM ratio tended to decrease as the stands matured. Vegetation OM contributed more to system OM than soil OM on mid-age and mature stands. The results showed that the amount of OM in the forest ecosystem has been doubled during the 30-year period.

Vegetation nutrients increased also as stand age increased. Nutrients were generally distributed equally in foliage, branches, bole bark, bole wood, and roots. Calcium content was exceptionally high in aspen bole bark because of high bark Ca concentration. It is typical in aspen stands that nutrients in bark is relatively high due to high bark biomass and nutrient concentrations(Alban *et al.*, 1978; Perala and Alban, 1982; Pastor and Bockheim, 1984). Aspen stands, particularly in this study, has been invaded by other tree species carrying greater biomass on branches. As a result of that, the aspen stands seemed to carry greater amount of nutrients in branches than any other plant tissue as they grew older. Nutrients in shrub layer did not change throughout all stand ages. In herbs, K was significantly higher than other nutrients. Herb nutrient content also did not change throughout all stand ages. Shrubs and herbs contributed less than 3 percent of the system nutrients.

Calcium and N were the most abundant nutrients in forest floor. Unlike other nutrients which remained same at different stand ages, forest floor N was greater in young stands than in older stands. The amount of N in surface soil was also greater in young stands than in older stands. In young stands, nutrient storage was greater in forest floor than in vegetation, except for K. Nutrient content in the soil was substantial even if the soil has shallow A horizon (6.2cm depth) and sandy soil texture. Soil contributed 70 to 95 percent of the total nutrients in the ecosystem, and from 30 to 65 percent as in available nutrients.

Nutrient fluxes

Calcium was the most abundant element measured in wet deposition, adding 10.7 kg ha^{-1} to the study site(Table 3). Other nutrients added to the site were in the order of total N, K, Mg, and total P. Precipitation nutrients measured in the present study were comparable with the data measured in the same region(Comerford and White, 1977; Verry and Timmons, 1977). However, atmospheric nutrient inputs estimated in the present study were greater than the values estimated in the past. According to the findings of Johnson and Lindberg(1992), bulk deposition measurements (with continuously open funnels or buckets) underestimates total nutrient deposition. By adding dry deposition, total atmospheric input of nutrients generally became twice of that from wet deposition.

Potential evapotranspiration(PET), calculated with a computer program developed by Black (1966), was 61.4cm yr^{-1} in the study site. The result was slightly higher than the PET measured in Wisconsin(Pastor and Bockheim, 1984). Actual evapotranspiration estimation was 52.1cm yr^{-1}, which was comparable to the 52cm yr^{-1} measured from an aspen stand on a Spodosol in Russia (Molchanov, 1963). Pan evaporation measured at the Cloquet Forestry Center was 37.6cm yr^{-1}. Nutrient leaching losses were relatively low at all study sites(Table 4). The amount of nutrient

Table 3. Nutrient concentrations in precipitation and total nutrient input by atmospheric deposition, standard errors are presented in the parenthesis.

Nutrient	Concentration		Atmospheric deposition*
	Rain	Snow	
	mg L^{-1}		kg ha^{-1}
Org. N	0.294 (0.024)	0.171 (0.033)	3.7
NH4-N	0.338 (0.072)	0.284 (0.053)	4.5
NO3-N	0.279 (0.051)	0.384 (0.042)	4.2
Total P	0.053 (0.009)	0.049 (0.015)	0.7
K	0.724 (0.014)	0.729 (0.005)	12.9
Ca	1.767 (0.218)	0.725 (0.268)	24.5
Mg	0.293 (0.049)	0.233 (0.033)	3.4

* Atmospheric deposition=Wet deposition+Dry deposition Dry deposition was estimated from wet to dry deposition ratio(W : D) of N(1), P(1), K(0.638), Ca(0.772), Mg(1.298)(Johnson and Lindberg, 1992)

Table 4. Mean growing season concentrations of soil solution at two depths in three different ages of aspen stands and nutrient leaching losses.

Nutient	Age class	Soil depth		Leaching loss
		0.5m	1m	
		mg L^{-1}		kg $ha^{-1}yr^{-1}$
	Mature	0.408 (0.203)	0.302 (0.043)	0.53
N	Mid-age	0.688 (0.231)	0.297 (0.156)	0.52
	Young	0.311 (0.062)	0.294 (0.071)	0.52
	Mature	0.024 (0.001)	0.024 (0.001)	0.04
P	Mid-age	0.024 (0.001)	0.025 (0.002)	0.04
	Young	0.025 (0.001)	0.024 (0.000)	0.04
	Mature	0.707 (0.001)	0.707 (0.001)	1.24
K	Mid-age	0.715 (0.001)	0.707 (0.001)	1.24
	Young	0.768 (0.002)	0.843 (0.086)	1.48
	Mature	1.265 (0.135)	1.621 (0.149)	2.85
Ca	Mid-age	1.580 (0.148)	2.121 (0.245)	3.73
	Young	1.370 (0.174)	2.164 (0.217)	3.81
	Mature	0.792 (0.061)	0.838 (0.053)	1.47
Mg	Mid-age	0.775 (0.054)	0.829 (0.039)	1.46
	Young	0.854 (0.055)	0.941 (0.041)	1.66

loss, with an exception of N, was greater than those reported for other aspen stands by Pastor and Bockheim(1984) in Wisconsin and by Timmons and co-workers(1977) in northern Minnesota, but lower than those estimated by Richardson and Lund(1975) in northern Michigan. Calcium was the most abundant nutrient in leaching solution. Except for N and P, nutrient leaching losses tended to increase in young stands. Atmospheric deposition of nutrients exceeded leaching loss at all stands. The results indicate that the aspen stands sequestered nutrients effectively within the ecosystem. Nutrient leaching losses are generally low in aspen forests compared to other temperate deciduous forests(Pastor, 1990; Likens *et al.*, 1971).

The magnitude of the nutrient flux through plant uptake and litterfall was significantly greater than that of nutrient input and output on entire ecosystem level(Table 5), which is typical of forest ecosystems(Cole and Rapp, 1981; Johnson and Todd, 1990). Annual litterfall was greater in older stands(Fig. 1). The amount of leaf litter, however, was not significantly different between the stands of different ages. Because of high nutrient concentrations in leaf litter of young stands, the amount of nutrients being returned by litterfall were not significantly different among the stands of different ages. Nutrient input by atmospheric deposition tended to be higher than nutrient accumulation in the vegetation of young stands. At mature stands, most of the nutrient input from atmospheric deposition was sequestered in the vegetation. Denitrification activity was minimal in all aspen stands due to low soil moisture and low soil carbon. Denitrification activity increased by two orders of magnitude when the soil was treated with a combination of KNO_3 and dextrose.

Weight loss from litterbags was 41 to 47 percent after 18 months(Fig. 2). The litterbag weight

Table 5. Estimated annual flux of nutrients (kg ha^{-1} yr^{-1}) in aspen stands at three different ages.

Nutrient flux	Mature	Mid-age	Young	Nutrient flux	Mature	Mid-age	Young
		N				Ca	
Deposition	12.40	12.40	12.40	Deposition	24.50	24.50	24.50
Mineralization	26.63	32.69	77.51	Soil weathering[1]	3.01	3.01	3.01
Plant uptake	59.97	43.30	52.52	Plant uptake	98.00	77.14	70.81
Litterfall	39.41	29.80	41.83	Litterfall	60.55	48.56	50.71
Plant sequester	20.56	13.50	10.69	Plant sequester	37.45	28.58	20.10
Soil leaching	0.34	0.33	0.33	Soil leaching	1.80	2.36	2.41
Denitrification	1.76	1.76	1.76				
Net soil budget	16.37	29.50	77.13	Net soil budget	-11.74	-3.43	5.00
		P				Mg	
Deposition	0.70	0.70	0.70	Deposition	3.40	3.40	3.40
Mineralization[2]	3.73	4.58	10.85	Soil weathering[1]	1.22	1.22	1.22
Plant uptake	18.28	11.07	9.16	Plant uptake	12.20	8.99	8.51
Litterfall	6.92	4.16	5.13	Litterfall	8.79	6.53	6.52
Plant sequester	11.36	6.91	4.03	Plant sequester	3.41	2.46	1.99
Soil leaching	0.03	0.03	0.03	Soil leaching	0.93	0.92	1.05
Net soil budget	-6.96	-1.66	7.49	Net soil budget	0.28	1.24	1.58
		K					
Deposition	12.90	12.90	12.90				
Soil weathering[1]	1.96	1.96	1.96				
Plant uptake	64.10	43.62	37.21				
Litterfall	16.70	14.26	17.39				
Plant sequester	47.40	29.36	19.82				
Soil leaching	0.79	0.79	0.94				
Net soil budget	-33.33	-15.29	-5.90				

[1] Soil weathering from Kolka and Grigal (in preparation)
[2] P mineralization was estimated from the ratio of N : P (1 : 0.14) in soil organic matter.

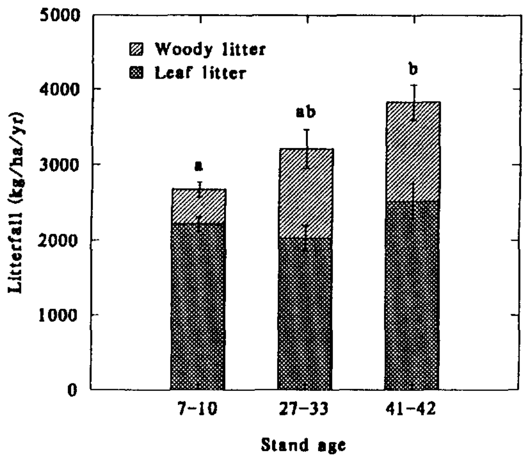

Fig. 1. Litterfall in the aspen study sites at three different stand ages. The same letter indicates that litterfall is not significantly different at alpha=0.05. The standard error of each mean is also presented.

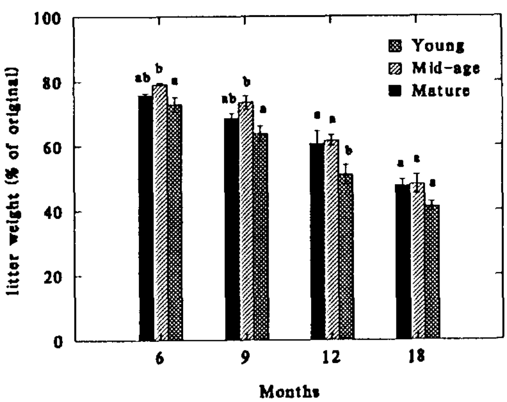

Fig. 2. Litter decomposition in the aspen study sites at three different stand ages. The same letter indicates that litter weight loss is not significantly different in each collection at alpha=0.05. The standard error of each mean is also presented.

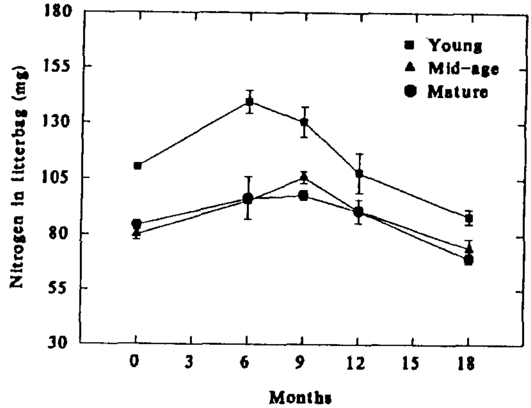

Fig. 3. Nitrogen changes in the litterbag buried in the aspen study sites at three different stand ages. The standard error of each mean is also presented.

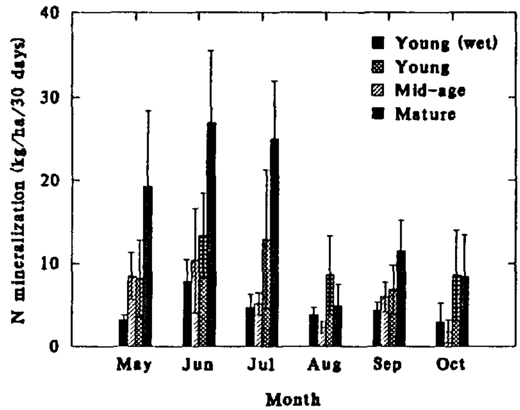

Fig. 4. Net nitrogen mineralization in the soil of aspen study sites at three different stand ages. The standard error of each mean is also presented.

loss during the first 6 months suggests that decomposing microorganisms were active under the snow during the winter months. Nitrogen and Ca concentrations, unlike other nutrients, increased significantly in the litterbags during the 18 months. While the litter weight loss was substantial, net N immobilization occurred in the litterbags during the first 12 months(Fig. 3). Net increase of N in litter is common in early stages of litterbag experiments(Boerner, 1984; Edmonds, 1984; Schlesinger and Hasey, 1981). Active heterotrophs with C : N ratio of 4 : 1 to 9 : 1(Buckman and Brady, 1960) demand large amounts of N and retain most of it while C is consumed as an energy source. This leads an increase in N concentration of litter in early stages of decomposition. Net N mineralization started after 12 months.

There were strong soil N mineralization activities at young, high water table sites during spring(Fig. 4). The activity started to fall down in August. There were large spatial variations in N mineralization in all study sites, especially in young stands. Nitrogen mineralization measured by in situ aerobic incubation is often balanced by

Table 6. Total and available nutrients in upper 30 cm of the soil in aspen stands at three different stand ages. Standard errors are presented in the paretheses.

Nutrient	Age class	Total	Available
		------ kg/ha ------	
N	Mature	1632(195)	126(21)
	Mid-age	1613(318)	104(7)
	Young	2092(279)	236(73)
P	Mature	1254(463)	230(33)
	Mid-age	1369(29)	256(4)
	Young	1478(248)	213(24)
K	Mature	7031(557)	195(6)
	Mid-age	8788(1669)	288(14)
	Young	3606(553)	234(37)
Ca	Mature	7307(670)	1543(104)
	Mid-age	8992(2185)	1342(98)
	Young	8742(1306)	2049(574)
Mg	Mature	7370(68)	227(26)
	Mid-age	9042(1541)	200(23)
	Young	7703(598)	217(42)

immobilization, and net mineral N production is minimal where soil N mineralization potential is low. The mean values presented in the figure incorporated both positive(mineralization) and negative(immobilization) rates of mineral N production. Net N mineralization rate was greatest in young stands and decreased as stands became older. The rate increased by 2 to 3 times in high water table sites. Soil N mineralization generally increases with increasing levels of soil moisture (Adams and Attiwill, 1986; Burger and Pritchett, 1984; Matson and Vitousek, 1981) until the conditions become unfavorable to the aerobic process. Nitrogen mineralization was apparently benefited from the increased soil moisture conditions in high water table sites of this study. Annual N mineralization was 1.5 to 3.2 percent of soil total N in the study site.

Available nutrients were relatively small compared to the total nutrients in the soil(Table 6). The availability of N and Ca was greater in young stands than in older stands. This increased level of available nutrients facilitated cycling of the nutrients in young stands. Available nutrients were 6-11% N, 14-18% P, 3-6% K, 15-23% Ca, and 2-3% Mg of total nutrients in upper 30cm of the soil.

The comparison of the components in nutrient cycling are subject to many uncertainties. Vegetation nutrient values are also subject to uncertainties in both biomass estimation and nutrient concentrations. Although the study sites were selected within a limited area on same soil types, there were spatial variation in soil physical and chemical properties. One of the main causes of variation was the physiographic condition of the site that decided water table depth. Despite the large sources of uncertainty, the nutrient values presented are useful to compare nutrient status at various stand ages.

Nutrients were being accumulated in the soil stratum of young stands that includes forest floor(Table 5). Nutrients, except for N and Mg, were being reduced in the soil of both mid-aged and mature stands and accumulated in the vegetation. Nitrogen and Mg have increased in the soil at all stand ages, but the scale was greatly reduced as in older stands. Nitrogen and Ca were the largest in quantity in nutrient cycling of the study site. Nutrient budget indicates the

Table 7. Nutrient budget for harvesting of the aspen stands with a 40-year rotation.

Item	N	P	K	Ca	Mg
			------------ hg/ha ------------		
Atmospheric input	496	28	516	980	136
Mineralization/weather	1065	149	78	120	49
Input total	1561	177	594	1100	185
Leaching loss	13	1	32	72	37
Accelerated leaching loss1	0	0	0	312	0
Removal by harvest	458	64	295	712	70
Output total	471	65	327	1096	107
Input/Output index	3.3	2.7	1.8	0.9	1.7

[1] Accelerated leaching loss for 5 years after harvesting(Silkworth and Grigal, 1982).

potential of the study site to support future harvests of the aspen(Table 7). Assuming that aspen stands in the study site are whole-tree harvested with a 40-year rotation, nutrient inputs are sufficient to support nutrient losses occurred by timber harvest. Calcium seems to be marginal and could be losing from the study site depending on the site conditions. Although there are reserves of available Ca in the soil, Ca would be exhausted in the study site in a long-term speculation.

LITERATURE CITED

1. Adams, M.A. and P.M. Attiwill. 1986. Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. Plant and Soil 92, 341-362.
2. Alban, D.H. 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil properties. Soil Sci. Soc. Am. J. 46: 853-861.
3. Alban, D.H. and D.A. Perala. 1990a. Ecosystem carbon following aspen harvesting in the upper Great Lakes. p.123-131. *In* R.D. Adams(ed.) Aspen symposium '89 proceedings. USDA, For. Serv. North Central For. Exp. Stn. Gen. Tech. Rep. NC-140.
4. Alban, D.H. and D.A. Perala. 1990b. Impact of aspen timber harvesting on soils. p.377-391. *In* S.P. Gessel, D.S. Lacate, G.F. Weetman, and R.F. Powers(eds.) Sustained productivity of forest soils. Proceedings of the 7th North American Forest Soils Conference, Univ. of British Columbia, Faculty of Forestry Publication, Vancouver, B.C.
5. Alban, D.H., D.A. Perala, and B.E. Schlaegel. 1978. Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. Can. J. For. Res. 8: 290-299.
6. Boerner, R.E. 1984. Nutrient fluxes in litterfall and decomposition in four forests along a gradient of soil fertility in southern Ohio. Can. J. For. Res. 14: 794-802.
7. Boyle, J.R. and A.R. Ek. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. For. Res. 2: 407-412.
8. Boyle, J.R., J.J. Phillips, and A.R. Ek. 1973. "Whole tree" harvesting: nutrient budget evaluation. J. Forestry 71: 760-762.
9. Buckman, H.O. and N.C. Brady. 1960. The nature and properties of soils. The MacMillian Co., New York, NY. 567p.
10. Burger, J.A. and W.L. Pritchett. 1984. Effects of clearfelling and site preparation on nitrogen mineralization in a southern pine stand. Soil Sci. Soc. Am. J. 48: 1432-1437.
11. Burton, D.L. ans E.C. Beauchamp. 1984. Field techniques using the acetylene blockage of nitrous oxide reduction to measure denitrification. Can. J. Soil Sci. 64: 555-562.
12. Cole, D.W. and W. Rapp. 1981. Elemental cycling in forest ecosystems. pp.341-409. *In* D.E. Reichle(ed.) Dynamic properties of forest ecosystems. Cambridge Univ. Press, London.
13. Comerford, N.B. and E.H. White. 1977. Nutrient content of throughfall in paper birch and red pine stands in northern Minnesota. Can. J. For. Res. 7: 556-561.
14. Edmonds, R.L. 1984. Long-term decomposition and nutrient dynamics in Pacific silver fir needles in western Washington. Can. J. For. Res. 14: 395-400.
15. Environmental Protection Agency. 1971. Methods for chemical analysis of water and wastes. EPA National Environmental Research Center, Analytical Quality Control Lab., Cincinatti, Ohio.
16. Federer, C.A., J.W. Hornbeck, L.M. Tritton, C.W. Martin, R.S. Pierce, and C.T. Smith. 1989. Long-term depletion of calcium and other nutrients in eastern US forests. Environ. Management 13: 593-601.
17. Hackett, R.L. and W.B. Smith. 1990. Pulpwood production in the North Central region. USDA For. Serv. North Central For. Exp. Stn. Resource Bulletin NC-123. 29p.
18. Hansen, E.A. and A.R. Harris. 1975. Validity of soil water samples collected with porous ceramic cups. Soil Sci. Soc. Am. Proc. 39: 528-536.
19. Johnson, D.W. and S.E. Lindberg(eds.). 1991. Atmospheric deposition and forest nu-

trient cycling: a synthesis of the integrated forest study. Springer-Verlag, New York, N.Y. p.707.
20. Johnson, D.W. and D.E. Todd. 1990. Nutrient cycling in forests of Walker Branch Watershed, Tennessee: Roles of uptake and leaching in causing soil changes. J. Environ. Qual. 19: 97-104.
21. Keays, J.L. and J.V. Hatton. 1975. The implication of full-forest utilization on world-wide supplies of wood by the year 2000. Pulp Pap. Inst. 17: 49-52.
22. Keeney, D.R. 1982. Nitrogen-availability indecies. pp.711-733. *In* A.L. Page, R.H. Miller, and D.R. Keeney(eds.) Methods of soil analysis, Part 2. Chemical and microbiological properties. Agronomy Monograph No. 9(2nd edition). American Society of Agronomy, Madison, WI.
23. Likens, G.E., F.H. Bormann, R.S. Pierce, J.S. Eaton, and N.M. Johnson. 1977. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York, NY.
24. Malkonen, E. 1976. Effect of whole tree harvesting on soil fertility. Silva Fenn. 10: 157-164.
25. Matson, P.A. and P.M. Vitousek. 1981. Nitrigen mineralization and nitrification potentials following clearcutting in the Hoosier National Forest, Indiana. For. Sci. 27: 781-791.
26. Molchanov, A.A. 1963. The hydrologic role of forests. Israel Program for Scientific Translations, National Technical Information Service, Washington, D.C.
27. Pastor, J. 1990. Nutrient cycling in aspen ecosystems. pp.21-38. *In* R.D. Adams(ed.) Aspen symposium '89 proceedings. USDA For. Serv. North Central For. Exp. Stn. Gen. Tech. Rep. NC-140. St. Paul, MN.
28. Pastor, J. and J.G. Bockheim. 1984. Distribution and cycling of nutrients in an aspen-mixed hardwood-spodosol in northern Wisconsin. Ecology 65: 339-353.
29. Perala, D.A. and D.H. Alban. 1993. Allometric biomass estimators for aspen ecosystems in the upper Great Lakes. USDA For. Serv. North Central For. Exp. Stn. Res. Pap.
30. Raison, R.J., M.J. Connell, and P.K. Khanna. 1987. Methodology for studying fluxes of soil mineral-N in situ. Soil Biol. Biochem. 19: 521-530.
31. Rapp, M., M. Cl. Leclerc and P. Lossaint. 1979. The nitrogen economy in a *Pinus pinea* L. stand. For. Ecol. Manag. 2: 221-231.
32. Richardson, C.J. and J.A. Lund. 1975. Effects of clearcutting on nutrient losses in aspen forests on three soil types in Michigan. pp.673-686. *In* F.G. Howell, J.B. Gentry, and M.H. Smith(eds.) Minneral cycling in southeastern ecosystems. Energy Research and Development Administration Symposium Series, National Technical Information Services, Springfield, VA.
33. Schlesinger, W.H. and M.M. Hasey. 1981. Decomposition of chaparral shrub forage: losses of organic and inorganic constituents from deciduous and evergreen leaves. Ecology 62: 762-774.
34. Shephard, J.P. and M.J. Mitchell. 1991. Solution chemistry in a red pine plantation thirty-nine years after potassium fertilization. Soil Sci. Soc. Am. J. 55: 1446-1452.
35. Silkworth, D.R. and D.F. Grigal. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46: 626-631.
36. Thornthwaite, C.W. and J.R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology, Vol. X, No. 3. Drexel Institute of Technology, Centerton, New Jersey.
37. Timmons, D.R., E.S. Verry, R.E. Burwell, and R.F. Holt. 1977. Nutrient transport in surface runoff and interflow from an aspen forest. J. Environ. Qual. 6: 188-192.
38. Verry, E.S. and D.R. Timmons. 1977. Precipitation nutrients in the open and under two forests in Minnesota. Can. J. For. Res. 7: 112-119.
39. Wagner, G.H. 1962. Use of porous ceramic cups to sample soil water within the profile. Soil Sci. 94: 379-386.