Summa ersion

July 1, 1993

LCMR WORK PROGRAM 1991

I. Impacts of intensified forest management and atmospheric change on nutrient cycling and tree species suitability

Program Manager:	Alan R. Ek Forest Resources University of Minnesota St. Paul, MN 55108 612/624-3400

A. M.L. 91, Ch.254, Art. 1, Sec. 14 Subd: 7(b)

Appropriation:	$220,000
Balance:	$0

Impacts on intensive forest management: This appropriation is to the University of Minnesota, Department of Forest Resources, to assess the role of nutrient cycling and associated management practices for sustainability of Minnesota's forest resources under scenarios of increased harvesting and atmospheric change.

B. Compatible data: Not applicable. However, standardization of measurements and recording will be a goal to facilitate wide use of the data and its use with research and other data bases such as those maintained by the Minnesota Land Management Information Center's geographic information center, the USDA Forest Service North Central Forest Experiment Station, the Great Lakes Forest Growth and Yield Cooperative, and other LCMR projects, notably those concerning old-growth forests, regeneration/management of oak forests and aspen decay models.

C. Match requirement: Not applicable.

II. NARRATIVE

Minnesota's forests will come under increasingly intensive management in the next several decades. That poses questions about the choice of forest stand rotation age that favors the sustainability and enhancement of soil and site productivity. At the same time, air quality changes, perhaps including changes in precipitation and temperature patterns, may impact fundamental plant and soil processes. Fundamental understanding of nutrient cycling processes and tree requirements is needed soon to deal effectively with the management questions concerning species-site matching, choice of rotation lengths and appropriate levels of tree and stand utilization. The question is complicated by the range of soils and ecosystems in the state and the fact that long term studies are essential to this research. Answers to the above questions have implications for understanding the dynamics of a variety of forest flora and fauna.

The proposed study has experimentation, monitoring and modelling components. However, there are important tradeoffs between these for a cost effective and penetrating project. Judicious experimentation and effective modelling will reduce the need for and cost of monitoring. Alternatively, monitoring serves as a data base for validation of the modelling. Objective A will collect data needed to refine the model chosen for use in the study. Objective C will use the data from objective A to modify and improve the model. Objective B will collect data to allow the extrapolation of model results to a wide range of sites. Objective B also sets the stage for state-wide extrapolation to be carried out in years 3-4. To the extent possible, extrapolation will be based on the results of the first two years, but some additional sampling of sites in years 3-4 will be necessary. The three objectives are described below. Specifications will be developed further and finalized in the spring of 1991.

III. OBJECTIVES

A. ESTIMATE SITE SPECIFIC IMPACTS OF TIMBER HARVESTING ON FOREST SOILS AND NUTRIENT CYCLING. (leaders: Grigal, Alban, Perala, Pastor, Sucoff)

A.1. Narrative: Intensive investigations of nutrient use efficiency are proposed for sites of different elemental capital. Investigations will be concentrated on aspen of two ages on three types of soils. Aspen was selected because it is the major species harvested in Minnesota and it is known to be nutrient demanding. Observations will include monitoring of tree growth, stand water balance, atmospheric deposition of nutrients, soil nutrient status, litter dynamics and biomass over a four to eight year period. Both undisturbed and fertilized plots will be examined. The emphasis will be on improving our understanding of nitrogen, calcium and carbon cycling and how these influence the response to harvest and potential atmospheric change

This study component is designed to collect sufficient data to refine the LINKAGES model discussed in part C. In particular we seek data to add a meaningful calcium availability module and a calcium response module to LINKAGES. We will stress the use of data from pre-existing USDA Forest Service study sites and add a poor site to complete the study matrix of sites. We would monitor fluxes in both young and mature stands, selecting those near weather stations. Additionally, fertilizer or stable isotopes might be added to some sites to allow estimation of annual turnovers, particularly of calcium. However, such isotope studies would not begin until year three or beyond, as the technique needs further development. The general hypotheses motivating the study design are that 1) repeated harvests have the potential to lower productivity through the depletion of calcium or nitrogen and 2) soil differences have a major predictable impact on sustainability. Specifically, a nutrient demanding tree species like aspen may be more difficult to manage on a sustainable basis on nutrient poor sites. The key is to quantify tree requirements over time and determine the ability of soils to supply these needs.

A.2. Procedures: An important step in the success of this study objective is to locate aspen on a site that will fill the most serious data gaps given existing installations. That choice will be a poor site where nutrients are expected to be limiting. Where possible, subject stands of other species will be located nearby for possible extension of the study to facilitate comparisons among species. Additional species including red pine and oak would be added, but only if more funds were available. As it stands, we would rely on cooperating studies by the USDA Forest Service for aspen, white spruce, paper birch and mixed aspen/ hardwood stands. The table below is suggestive of the study design:

Cover type/age class	Soil		
	Poor	Light	Heavy
Aspen young	x	x[c]	x[c]
mature	x	x[c]	x[c]

[c] Existing cooperator sites (USDA Forest Service, Cloquet and Pike Bay, Minnesota)

The poor aspen site (poor in N and Ca) provided by this proposal will add considerable leverage to the inference capability provided by the existing sites. Data collection efforts on these six stands are referred to as the intensive study.

Each cell in the chart above, i.e., each soil and age combination, would involve study sites of a minimum of 2 hectares in size upon which we would collect and examine data as described in the next paragraph. In effect, we would seek two locations (landform x soil combinations) that have stands of both ages in close proximity. The young stands, in effect, would describe site and stand conditions and development following harvesting. This would be a stand harvested in the last five years. The mature stand would be chosen to approximate pre harvest conditions and processes. Candidate sites are available within 75 miles of the Cloquet Forestry Center and will be located in the spring of 1991.

Data to be considered for collection would include:

- Site and stand history
- Aerial photography (historical and new large scale for crown mapping)
- Landform/physiographic condition
- Soils and soil mapping unit data
- Climatological data including solar radiation
  (from nearby weather station)
- Water balance (evapo-transpiration, leaching, runoff, etc.
- Overstory and understory vegetation monitoring plots
  (every other year beginning in 1991)
- Biomass and tissue nutrient content
- Atmospheric deposition of nutrients
- Litterfall
- Litter decomposition
- Fine root biomass
- Effective rooting depth
- Soil physical properties
- Soil chemistry by major horizon
  (Ca,Mg,N,P,K and C every fourth year beginning in 1991)
- Soil solution chemistry (monthly)
- Total analysis of soil (soil mineralogy)

In general, study procedures would follow those described by Alban and Perala (1989) for ongoing studies of nutrient and carbon dynamics at several sites in the Lakes States. Using similar procedures would ensure compatibility of various study data and broaden the base for inference. The intensive study will provide physiological justification for modelling direction and knowledge of soil changes after harvesting, ecosystem storage pools, annual dynamics of the systems considered and how the sites (3) differ in storage and dynamics. However, there is a need to focus the set of variables and to assess the most cost effective way to observe them. Thus detailed procedure specification is an important early portion of the study. Some possible exceptions and additions to previous procedure are described below.

The overstory monitoring plots (four @ 0.05 hectares for each cell in the above table) for observation of trees greater than 1.3 m in height would include species, diameter at breast height (dbh), biomass, leaf area, etc. The understory vegetation monitoring plots (at least five @ $4m^2$) would be situated within the overstory plot for observation of species, density and biomass of small trees, shrubs and herbaceous vegetation. Aspen clones will be identified by morphology and phenology.

Additional information will be collected on soils with to quantify a) mineral weathering component of nutrient availability (leaders: Grigal, Cooper) and b) growth responses (leaders: Grigal, Sucoff). For nutrient availability, we will model and measure nutrient fluxes at the effective rooting zone. Lysimeter solution chemistry will be linked with hydrologic flux. We will determine N availability by measuring its mineralization rate with buried resin bags and/or soil cores. This rate is highly correlated with productivity. For calcium, we will collect data needed to refine and use pre-existing models of weathering rates of soil minerals. Those models have been developed in Scandinavia to assess the impacts of acid deposition on forests. Needed data include soil mineral composition, surface area, and soil solution chemistry. The proposed intensive site on a poor soil, the pre-existing USDA Forest Service sites and supplemental sites included under the gradient study described below will be sampled to provide the data to allow parameterization of the model. After parameterization, a simplified form of the model will be integrated into LINKAGES. This effort to quantify nutrient availability is designated the weathering study.

The responses of aspen to nitrogen and calcium singly and in combination will be determined in sufficient detail to be incorporated into the LINKAGES model. These responses will be determined in two ways: a fertilizer experiment and a gradient analysis of aspen stands across the region. The fertilizer and the gradient study will then be integrated to provide the response equations demanded by the model.

The need for developing response functions is illustrated by the paradox as to which nutrient limits growth of aspen. Fertilizer trials have always indicated nitrogen limitation. On the other hand, nutrient budget calculations that compare nutrient removals in harvested biomass with reserves in soil often show that calcium may become limiting. Consequently, data will be collected and analyzed using a combination of traditional approaches and recent physiologic understanding of calcium function and transport.

Summers, K., S. Gherini, R. Munson, R. Hudson, D. Johnson, and L. Pitelka. 1990. The IFS nutrient cycling model: overview and application. TetraTech, Lafayette, CA. Unpublished mimeo.

Sverdrup, H. and P. Warfvinge. 1990. Modelling chemical weathering rates of primary silicate minerals: Consistency between observed field rates and model predictions. Unpublished mimeo.

Timmer, V. R. and E. L. Stone. 1978. Comparative foliar analysis of young balsam fir fertilized with NPK and lime. Soil Sci. Soc. Am. J. 42:125-130.

Van Cleve, K. and L. K. Oliver. 1982. Growth response of postfire quaking aspen to N, P and K fertilization. Can. J. Forest Res. 6:145-152.

Walters, D.K., and A.R. Ek. 1989. General guidelines for the installation and measurement of permanent forest inventory plots. Univ. Minnesota Dept. Forest Resources, Great Lakes Forest Growth and Yield Cooperative Pub. No. 1. 6p. plus appendix.

White, E. H. 1974. Whole-tree harvesting depletes soil nutrients. Can. J. Forest Res. 4:530-535.

A.3. Budget:

	LCMR funds	Matching funds
Amount Budgeted:	$160,000	$0
Balance:	$0	$0

A.4. Timeline for Products/Tasks

```
                                     Jan91  Jul91   Jan92  Jun92  Jan93  Jun93

Literature review and specification
     of detailed procedure  -------------|
Study site identification   -------------|
Observation of initial conditions  -------|
Monitoring apparatus installation  -----|
Field data collection       -----------------------------------------------------|...
     -intensive study
     -weathering study
     -fertilizer study
     -gradient study
Laboratory analysis            ------------------------------------------------|...
Synthesis                                     ---------------|    ------------|...
```

A.5. Status:

First status report for January 1, 1992: Study sites have been identified and field sample collections are completed for the weathering and the gradient study and the samples are being analyzed in the laboratory. Eight study plots and corresponding subplots (four in each plot) are established for the intensive study and nine plots have been established for the fertilizer study. Plot monitoring equipment/procedure has also been installed and implemented. We are now in the data collection phase for the intensive and fertilizer studies. Fertilization is planned from early spring 1992 with subsequent applications to be determined. Laboratory data analysis has also begun.

Second status report for July 1, 1992: Laboratory analysis of the gradient study samples is completed and weathering study samples are being analyzed in the laboratory. The sample analysis will be completed for the weathering study in summer 1992. Plot monitoring and data collection discontinued last fall has been resumed for the intensive study sites. Sample and data collection will be continued for the intensive study throughout the growing season of 1992. Fertilizer was applied to study plots in spring 1992 and a subsequent application is planned in summer 1992. Laboratory data analysis has also begun for the intensive study sites. Laboratory equipment shortages have been largely overcome at the cost of additional labor and equipment sharing arrangements. A problem with beaver damage on some study plots is being addressed.

Third status report for January 1, 1993: Data collection and sample processing are completed and data are now being entered. Soil (forest floor and surface mineral soil) and plant tissue (wood and bark) samples were collected at three points in each of 30 stands. Stands were located between Brule, WI and Bemidji, MN. In addition, tree diameter, basal area, stand age, and height data were characterized at each sampling point. Data analyses will begin immediately after completion of data entry. Analyses will concentrate on characterizing relationships between soil Ca and tissue Ca, tissue Ca and site productivity, and ultimately soil Ca and site productivity.

Soil samples were collected from 29 horizons of five aspen sites for weathering study. The samples are analyzed for soil physical and chemical properties. X-ray diffraction and elemental analyses of clays and silts are completed and clay mineralogy is being determined. A computer model (PROFILE) simulations of weathering rates is being applied to the collected data. The PROFILE model runs will be done for each soil. The calcium profile depletion study has variable results due to changes in soil parent materials. Mineralogy of the silts and/or the elemental profile may be used to develop the long-term weathering rates.

Most field sample collection is completed from 8 stands (two 40-year-old, two 30-year-old, four 10-year-old stands) for intensive study. Precipitation samples will be collected until spring of 1993. Nutrient analysis of the collected precipitation, plant, forest litter, soil, and soil water samples is scheduled during winter and spring of 1993. Efforts of avoiding beaver damages are being continued with trapping and fencing in the study area where a beaver pond is in the vicinity.

Total of 90 kg N/ha of ammonium nitrate and 130 kg Ca/ha of calcium chloride were applied on the fertilization study sites in 1992. Same amount of fertilizer will be applied in spring of 1993. Growth response to the fertilizer was measured in fall of 1992. Leaf samples were collected for foliar diagnosis of nutrient status. Although vegetation growth responses to fertilizer may not be significant in the first year, we attempted to collect one-year results to provide informations for final report scheduled on June 30, 1993. The results after the first year will be collected providing further research funds are secured. Some plots which have been damaged by hares are fenced to prevent further damage.

The fertilizer study (leader: Sucoff) will be conducted on two sites deficient in both nitrogen and calcium and on two sites with moderate levels of nitrogen and calcium. Two of these installations will be located on the intensive study sites, notably the poor and light soils. The other two will be installed on soils equivalent to these sites. Small areas will be treated with a range of calcium and nitrogen levels and ratios. For cost effectiveness, the fertilizer treatments will be applied to individual trees. The responses will likewise be measured on individual trees, with each treatment replicated 10 to 15 times on each site. On each single tree plot the following variables will be measured:

- Tissue (leaves, bark, wood) Ca, N and other essential elements (pretreatment and annually, with several trees measured both in spring and late summer)
- Growth response to treatment

On each site involved, the following variables will be measured:

- Soil solution N, Ca (periodic)
- N with resin bags (periodic)
- Physical properties of the soil
- Chemical properties of the soil
- Climatological variables

The gradient study (leader: Grigal, Sucoff) will include the study sites in objective A and a number of the sites identified under objective B. The intent is to examine aspen stands geographically situated across Minnesota and the region. The purpose is to determine how productivity of aspen stands is associated with calcium and nitrogen levels in tree leaves, bark, wood and soil. Although a range of upland sites will be sampled, the emphasis will be on sites which are of likely to be low in calcium and nitrogen and on sites which are of low productivity. On each site the following variables will be measured:

- Tissue (leaves, bark, wood) Ca, N and other essential elements (sampled in late summer)
- A measure of soil Ca and N which will correspond to available Ca and N
- Tree biomass and age
- Annual climate during years since establishment

The data from the fertilizer and gradient studies, like the intensive study, will be analyzed to develop response curves and the identification of deficient elements.

In important exception to past procedure, we will emphasize the use of sampling and existing data including relationships (equations) from the literature to reduce costs and allow focus on the key processes (nutrient storage and availability) we seek to understand. Thus sampling and the construction of relationships between easily measured variables and more difficult to assess ones will be utilized extensively. Also, overstory biomass estimation will rely heavily on biomass/tree dimension relationships in the literature rather than destructive sampling.

There is already information on direct nutrient and carbon removals from harvesting and we will not duplicate that work. Throughfall and stemflow are other variables where literature values or substitution of soil solution and litter sampling will be cost effective.

References on background and procedure are:

Alban, D. H. 1982. Effects of nutrient accumulation by aspen, spruce and pine on soil properties. Soil Sci. Soc. Am. J. 46 (4): 853-861.

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. Forest Res. 8:290-299.

Alban, D. H. and D. A. Perala. 1990. Ecosystem carbon following aspen harvesting in the upper Great Lakes. In: Aspen Symposium Proc. '89. USDA Forest Service Gen. Tech. Rep. NC-140. pp: 123-131.

Binkley, D. 1984. Ion exchange resin bags: factors affecting estimates of nitrogen availability. Soil Sci. Soc. Am. J. 47:1050-1052.

Binkley, D., J. D. Aber, J. Pastor and K. Nadelhoffer. 1986. Nitrogen availability in some Wisconsin forests: Comparisons of resin bags and on-site incubators. Biol. and Fert. of Soils 2:77-82.

Boyle, J. R. and A. R. Ek. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. Forest Res. 2:407-412.

Eno, C. F. 1960. Nitrate production in the field by incubating the soil in polyethylene bags. Soil Soc. Soc. Am. Proc. 24:277-299.

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 U.S. forests. Environ. Mgmt. 13(5):593-601.

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. Environmental Quality. 19:97-104.

Minnesota Department of Natural Resources. 1989. An evaluation of the potential for calcium depletion in aspen sites in Minnesota. Division of Forestry, Forest Soils Unit. 12p.

Pastor, J., J. D. Aber, C. A. McClaugherty and J. M. Melillo. 1984. Above ground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin, Ecology 65:256-268.

Pastor, J. and J. G. Bockheim. 1984. Distribution and cycling of nutrients in aspen-mixed hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65:339-353.

Perala, D. A. and A. H. Alban. 1982. Biomass, nutrient distribution, and litterfall in *Populus, Pinus and Picea* stands on two different soils in Minnesota. Plant Soil 64:177-192.

Ruark, G. A. and J. C. Bockheim. 1987. Biomass, net primary production, and nutrient distribution for an age sequence of *Populus tremuloides* ecosystems. Can. J. Forest Res. 18:433-443.

Silkworth, D. R. and D. F. Grigal. 1982. Determining and evaluating nutrient losses following whole tree harvesting. Soil Sci. Soc. Am. J. 46:626-631.

Final status report for July 1, 1993: Soil and plant tissue samples were collected from 30 mature aspen stands located between Brule, WI and Bemidji, MN. Each stand was characterized by stand age, tree diameter, height, and stand basal area. Collected data were analyzed to investigate the relationships between soil Ca, tissue Ca, and site productivity. Study results showed a significant, positive correlation between Soil Ca levels and tissue Ca concentrations and between Soil Ca and site productivity. The results may indicate that increased Ca availability in the soil can lead to increased Ca uptake and accumulation in woody tissues which can ultimately be related to greater productivity. Other site properties may also be correlated with soil Ca, including the availability of other nutrients and of soil water.

Soil samples collected from five aspen sites in Minnesota and Wisconsin were analyzed to quantify weathering rates. Four methods used to estimate cation release rates were compared in this study. Soil solution method, which measures the flux of cations in the soil solution leaving the root zone was the least accurate method of the four because of the number and kinds of assumptions necessary to calculate the weathering rate. Batch methods that involve stirring and shaking of the soil and extracting cations with Sr and Rb solution were more accurate than those determined with the soil solution method. Mineralogical methods estimate depletion of primary minerals and elements in soils since the last glaciation. Although many assumptions are associated with mineralogical methods, the validity of those assumptions are greater than with the assumptions involved in the soil solution and batch methods. The effort necessary to run the computer model PROFILE was greater than for all other methods. Further, the output of the model, only the sum of cations, was the least useful result compared to those from other methods. Based on a variety of techniques, mean cation release rates in the aspen sites were Ca 1.6-3.8 kg ha^{-1} yr^{-1}, Mg 0.7-1.8 kg ha^{-1} yr^{-1}, and K 0.8-1.9 kg ha^{-1} yr^{-1}.

Nutrient status and nutrient cycling was investigated in eight aspen stands growing on sandy soils in Minnesota with stand ages from 7 to 42 years. Data collected from the study sites are in a form that can be accessed easily for further research. Nutrients added to the ecosystem by atmospheric deposition and soil weathering was efficiently stored in tree biomass. Nutrient leaching loss was low on all study sites. Nitrogen loss by denitrification was limited in the study sites due to low carbon and moisture in the soil. Nutrient cycling via litterfall greatly exceeded the nutrient fluxes into and out of the ecosystem. The amount of nutrient return by litterfall was in the same range for all stand ages, indicating the internal cycling of nutrients in young stands was as active as that in mature stands. Litter decomposition and nutrient release were faster in young stands. Likewise, nutrient availability was greater in young stands and became less as the stands grew older. Soil nitrogen mineralization was significantly higher in young stands. Sites with high water table retained more moisture in top soil and led the nitrogen mineralization rates greater than the rates in other sites. Study results indicate that nutrient cycling process was accelerated in young aspen stands with an increased level of available nutrients. Based on the nutrient balance of the aspen stands and estimated removal of nutrients by harvesting, calcium is the most critical element which is likely to be depleted if aspen stands are intensively harvested with short rotations.

The fertilization study was concerned with determining the effects of N and Ca depletion upon the growth of aspen. The responses to N and Ca fertilizers of young and mid-aged stands on sandy soils were examined. Only one year of results are available and it requires 4 years before any conclusions can be drawn. Thus remeasurements are planned for the future. Added Ca did not improve growth on any of the sites during the first year after fertilization. Added N may have improved growth on most sites, but the increase was only statistically significant in young stands on one of the soils. A preliminary pot study indicated that most of the nutrients and the nutrient balance of the entire stand depends on the A horizon of the soil.

A.6. Benefits: Knowledge gained would allow estimation of the process of nutrient cycling including inputs and outputs and outputs under different specie-site and management situations. The results would be inputs to the calibration and validation of the models in objective C.

B. ESTIMATING STATEWIDE IMPACTS (leaders: Burk, Cooper)

B.1. Narrative: Important to the analysis of harvesting impacts across the state is knowledge of what site specific study impacts imply for broad landform, soil and forest type combinations. For years one and two of the study the objective will be to validate the models developed in objective C by applying them to a limited number of sites. This work will provide the background for use of the models plus measurements on additional sites in years three and four of the study. The goal for model usage in these later years is extrapolation to a state-wide basis. Achieving this goal will involve use of geographic information systems (GIS) and synthesis of landform, soil type, forest cover type and harvesting patterns statewide. These same (objective B) sites would also be used as necessary to conduct the gradient study and possibly part of the fertilizer study described under objective A.

B.2. Procedures: In the first two years, existing reports and unpublished data from files would be acquired for model application. As part of that, the major geomorphic regions of the state and respective portions of commercial forest land would be identified. This would separate parent material and landform combinations and probably result in 15-20 regions. Subsequently information on vegetation and soil characteristics would be obtained for 2 to 5 sites chosen to represent some of these regions. These 2 to 5 sites will be measured to provide a basis for model parameterization and application for validation trials. Specifically, we would select stands of the major forest types on each soil type in a region to cover young, intermediate and mature age classes. This would provide data for an age based cross-section analysis to approximate how individual stands might develop over time. In years three through four this sample of sites would be expanded to approximately 20-30 to cover more of the parent material and landform combinations present.

Each site will be a minimum of two hectares in size. At each selected site the nutrient status of the vegetation (concentrating mainly on aspen) and soil will be assessed. This data collection will occur on two 0.05 hectare plots established at each site. Tree overstory information collected will include stem wood and bark samples (cores) and leaf tissue samples from six trees on each plot to be analyzed in the lab for nutrient content. Likewise, soil samples will be taken from each plot for nutrient analysis. Samples for a given site will be pooled for analysis. These and other observations would be similar to those collected under objective A, but with less frequent and/or less intense sampling. Again, sampling and existing data and relationships would be used judiciously to control costs. Specific measurement requirements could be refined as work on objective C progresses.

Observations made on these 20-30 sites will ultimately be used as inputs to the model of objective C to develop large area scenarios in the third and fourth years of the study. The GIS will be used to expand the study site results to larger areas. In effect the GIS will allow these data to be correlated with soil, vegetation, climatic, hydrologic and other layers in a statewide geographic information system (see following paragraph) and subsequent extrapolation of impacts of harvesting scenarios as described under objective C. The study areas under objective A would be a subset of these sites.

Reference data for geographic information system analysis will be assembled (or augmented as it may already exist) to include landform, soil type, and forest type data. Much of that is or will be available from other research or projects in the University (including LCMR projects), the Land Management Information Center (LMIC) and the Department of Natural Resources. The GIS will provide estimates of the areal extent of various landform combinations for aspen stocked areas. Based on preliminary results from objectives A and C, various landform and soil type strata thought to represent different potentials of nutrient deficiencies will be defined. To the extent the GIS (and associated data) are organized early, it will also be used to identify potential locations to sample according to the study design specifications.

References on motivation and procedure are:

Bates, P. C., C. R. Blinn and A. Alm. 1989. A survey of the histories of some poorly regenerated aspen stands in northern Minnesota. In: Proc. Aspen Symp. '89. USDA Forest Service Gen. Tech. Rep. NC-140.

Daddow, R. L. and G. E. Warrington. 1983. Growth-limiting soil bulk densities as influenced by soil texture. USDA Forest Service Watershed Systems Dev. Group, Fort Collins, CO. Report WSDG-TN-0005. 17 p.

Ruark, G. A., D. L. Mader and T. Q. Tatter. 1982. The influence of soil compaction and aeration on the root growth and vigor of trees - a literature review. Part 1. Arbor. J. 6: 251-265.

Shields, W. J.,Jr. and J. G. Bockheim. 1981. Deterioration of trembling aspen clones in the Great Lakes Region. Can. J. Forest Res. 11:530-537.

B.3. Budget:

	LCMR funds	Matching funds
Amount Budgeted:	$34,000	$0
Balance:	$0	$0

B.4. Timeline for Products/Tasks:

```
                             Jan91  Jul91  Jan92  Jun92  Jan93  Jun93

Study site identification    -------------|
Field observations                  ------|        -------|        ---|...
Laboratory analysis                        ---------------------------|...
Synthesis                                          -------------------|...
```

B.5. Status:

First status report for January 1, 1992: The field work for this objective has been moved to the summer of 1992 and beyond to take advantage of first year findings for both design factors and optimizing location of study plots. We do not expect this to alter the timeline for synthesis of this effort.

Second status report for July 1, 1992: Ten soil series which are representative of the soils supporting aspen forests in Minnesota have been identified. Detailed field sampling and measurement procedures have also been developed to assess these. Vegetation data and soil samples from a sample of aspen stands on these sites on these soils are now being collected and those efforts will continue throughout the summer of 1992.

Third status report for January 1, 1993: A total of 26 subplots were established and sampled during the summer and fall field season of 1992 at 13 locations. Sites 3, 6, and 8 contained young aspen stands with the remaining stands greater than 40 years old. Most stands had significant components of other tree species. Site indices ranged from 16 to 23 m (50 yr) and stand age ranged from 45 to 110 years with 3 subplots in recent clearcuts. Soils were selected to represent those that might have nutrient limiting constraints to long-term productivity and to represent a range in climatic parameters that exist across the state for aspen. The range of soil textures for plant materials included: four locations sandy, five locations coarse-loamy, two locations silty over rock, one location fine loamy, and one location clayey. Soil drainage differences between subplots in the same stands will be used to examine the effect of soil drainage on site productivity. A loamy substratum in some sandy locations will likely reduce the effect of the low water holding capacity parent material on productivity and is a common occurrence in outwash parent materials. Collected plant and soil samples are being analyzed for nutrients in the laboratory.

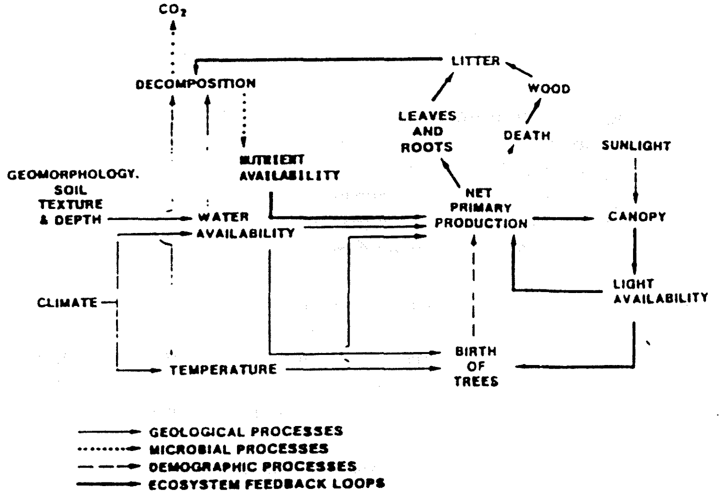
Final status report for July 1, 1993: Twenty-six subplots were sampled and measured in 13 locations. At the age of 40 years or older, most aspen stands had significant components of the other tree species. Soils were likely to have nutrient-limiting constraints to long-term productivity. Collected soil samples were analyzed for bulk density, percent clay, organic carbon, soil pH, effective CEC, and nutrients. Soil characteristics determined in the laboratory indicate that the sites include a wide range of physical, chemical, and soil morphologic parameters. Soil and aspen stand data are now in a form that can be accessed by users and will provide data necessary to the requirements of forest growth modelling studies.

B.6. Benefits: Provide a basis for extrapolation from the intensive studies in objective A to region and statewide conditions and to provide inputs to the model in objective C for scenario development over the next several decades given anticipated forest management intensification and atmospheric change scenarios.

C. MODELLING ALTERNATIVE MANAGEMENT SCENARIOS (leaders: Burk, Ek, Pastor, Phillips)

C.1. Narrative: This objective would incorporate study results as refinements of a model of forest growth and nutrient cycling dynamics. That modelling capability would be essential to long term (2-10 decade) simulation and study of the implication of rotation length choice together with potential atmospheric changes. It should also assist in shorter term projections. The model must also help translate research results to resource managers in a manner that facilitates informed applications in management.

C.2. Procedures: Many models have been developed for the purpose of quantifying growth and yield for timber management. Many others have been developed to describe forest succession of long time periods. We propose to utilize portions of the recent LINKAGES succession or gap model and portions of the STEMS regional forest growth model. A schematic of the hypothesized feedbacks and linkages in the resulting model is shown below:



The LINKAGES model also incorporates rudiments of soil processes including soil moisture, carbon and nutrient cycling. We would add components of other models, such as those being developed for nutrient flux and those with physiologically based characterizations of growth. A major refinement of LINKAGES will be the addition of two modules, one dealing with the availability of calcium to trees and the other with the response of trees to calcium. The corresponding modules or models to be integrated with LINKAGES include a new model of mineral weathering, and NuCM, a model of cation cycling in forests. In addition we will use the data collected and analyzed under objective A on the growth response of aspen to calcium and nitrogen to refine the growth response component of the model. The intent is also to facilitate use of radiation, temperature, and moisture (including transpiration) in the model. However, incorporating that detail will also require significant scale up procedures to be practical. The aim is a composite model useful to forestry practice with biological and ecological realism and statistical precision.

The resulting model will be an individual tree based simulator with some capability for treating vegetation, soil and climate interactions. Tree growth will be affected by nutrient availability, light, soil moisture, or degree days, whichever is most restrictive for each tree. Decomposition of litter in the model will be influenced by species and climate and help determine nutrient availability. The model will go beyond existing ones in incorporating the following specific aspects:

- Concise and accurate description of the known biology of the system
- Improved characterization of soil, and weather impacts on growth and succession including
    - Mineral weathering including calcium
    - Multinutient tree response model including calcium
- Biometrical precision
- Output which promotes wide usage and understanding of succession and growth and acid deposition and climate change implications
- Rapid execution to facilitate use with large data sets corresponding to initial conditions
- A framework which facilitates incorporation of growth/CO_2 functions

In developing the model, communication with the co-investigators working on objectives A and B is essential to ensure that needed model inputs are developed by the field studies. Starting with existing equation forms, models will be developed with appropriate statistical techniques which show the relationship between growth, stand and tree level variables, soil and weather variables. These techniques will involve linear, nonlinear, and time-series analyses. As the model is refined from study site data, statistical resampling procedures will be used as a means of prediction evaluation.

Given recent measurements of the USDA Forest Service Forest Inventory and Analysis (FIA) plots statewide and several forest management and climate change scenarios, forest impact predictions will be generated for the state using the new composite model. This involves applying the model to FIA data initial conditions and using the most accepted climate scenarios and associated atmospheric conditions. The scenarios will also be displayed and studied using the geographic information system layers described under objective B.
In developing those scenarios, we would attempt to develop a matrix of responses based on combinations of temperature, precipitation and CO_2. We would also develop such scenarios for alternative harvest utilization practices and various species site matching. Results would also be assembled in standard FIA tables

describing future forests in terms of variables of commercial and ecological interest. Additionally, results would be illustrated by maps via the geographic information system in the University's Remote Sensing Laboratory.

References on these models and procedures are:

Burk, T. E., R. Sievanen, and A. R. Ek. 1990. Construction of forest growth models based on physiological principles. In: Aspen Symposium Proc. '89. USDA Forest Service Gen. Tech. Rept. NC-140. pp: 103-111.

Belcher, D. M. 1981. User's guide to STEMS (Stand and Tree Evaluation and Modeling System). USDA Forest Serv. Gen. Tech. Rep. NC-70, 49p.

Botkin, D. B., J. F. Janak, and J. R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. J. Ecology 60(3):849-872.

Burk, T. E. 1988. Prediction error evaluation. In: Forest simulation systems. Proceedings of IUFRO Conference. L. C. Wensel and G. S. Biging, Eds. Univ. CA, Div. Agric. and Natural Resources, Bull. 1927. pp. 81-88.

Cleary, B. D. and R. H. Waring. 1969. Temperature: collection of data and its analysis for the interpretation of plant growth and distribution. Can. J. Botany 47:167-173.

Cook, E. R. 1987. The use and limitations of dendrochronology in studying effects of air pollution on forests. In: Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems. T. C. Hutchinson and K.M. Meema (eds.) NATA ASI Series, Vol. G16, pp. 277-290.

Davis, M. B. and D. B. Botkin. 1985. Sensitivity of cool temperate forests and their fossil pollen record to rapid temperature change. Quaternary Res. 23: 327-340.

Eriksson, M. E. 1989. Integrating forest growth and dendrochronological methodologies. Ph.D. Thesis, Univ. Minn., St. Paul, MN. 303p.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecological Monographs 53.

Olson, J. S., J. A. Watts, and L. J. Allison. 1983. Carbon in live vegetation of major world ecosystems. ORNL-5862. Oak Ridge National Lab., Oak Ridge, TN.

Pastor, J. and W. M. Post. 1985. Development of a linked forest productivity-soil process model. Oak Ridge National Lab., Environ. Sci. Div. Pub. No. 2455. 162p.

Pastor, J. and W. M. Post. 1986. Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. Biogeochemistry 2:3-27.

Pastor, J. and W. M. Post. 1988. Response of northern forests to CO_2-induced climate change. Nature 334:55-58.

Post, W. M. and J. Pastor. 1989. An individual-based forest ecosystem model for projecting forest response to nutrient cycling and climate changes. In: Forest simulation systems. Proc. IUFRO Conf. L. C. Wensel and G. S. Biging, Eds. Univ. CA, Div. Agric. and Nat. Res. Bull. 1927. pp. 61-74.

Reed, K. L. and R. H. Waring. 1974. Coupling of environment to plant response: a simulation model of transpiration. Ecology 55:62-72.

Shugart, H. H., S. B. McLaughlin, and D. C. West. 1980. Forest models: their development and potential applications for air pollution effects research. IN: Presented at Symp. on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems, June 22-27, 1980, Riverside, CA.

Smith, W. H. 1985. Forest Quality and Air Quality. J. Forestry 83(2):82-92.

Solomon, A. M. and H. H. Shugart. 1984. Integrating forest-stand simulations with paleoecological records to examine long-term forest dynamics. Pp. 333-356 in Agren, G.I. (ed.). State and Change of forest Ecosystems. Swedish Univ. Agric. Sciences Rep. Nr. 13. Uppsala, Sweden.

Solomon, A. M. 1986. Transient response modelling of forests to CO_2-induced climate change:simulation modelling experiments in eastern North America. Oecologia 68:557-569.

Summers, K., S. Gherini, R. Munson, R. Hudson, D. Johnson, and L. Pitelka. 1990. The IFS nutrient cycling model: overview and application. TetraTech, Lafayette, CA. Unpublished mimeo.

Sverdrup, H. and P. Warfvinge. 1990. Modelling chemical weathering rates of primary silicate minerals: Consistency between observed field rates and model predictions. Unpublished mimeo.

C.3. Budget:

	LCMR funds	Matching funds
Amount Budgeted:	$26,000	$3,000
Balance:	$0	$0

C.4. Timeline for Products/Tasks:

	Jan91	Jul91	Jan92	Jun92	Jan93	Jun93
Literature review	--------|					
Model refinement		----------------|				
Calibration			----------|			
Validation			-------------------|			
Scenario development					---------------|	
Synthesis					------------|	

C.5. Status:

First status report for January 1, 1992: Literature review has begun and modelling strategy has been developed. That strategy will emphasize a LINKAGES like individual tree based model including 3-4 soil layers as a below ground part and with a variable time step from days to one year. Below ground submodels from other studies have also been obtained for possible augmentation of the present framework.

Second status report for July 1, 1992: The overall modelling strategy has been refined. A LINKAGES like individual tree based model will be coded with a variable time step from minutes to one year. The below ground portion of the model will be developed as submodels modified from other studies in the U.S., Canada and Scandanavia. One below ground model being examined for usage is NuCM. That and other below ground submodels have been obtained and are under study for possible refinement and implementation into the project modelling framework. A number of scientists in the region have been asked to review and provide suggestions for the modelling framework. Staffing arrangements have been made to code the model during the coming summer.

Third status report for January 1, 1993: A major effort is nearing completion in the implementation of the LINKAGES ecosystem model. Much of the existing LINKAGES code was restructured and modularized to allow: 1) use of the program on a wider variety of workstation platforms including personal computers running DOS and 2) more straightforward replacement of submodels relevant to the present project. Submodels to be replaced are those for which relevant experimental evidence is being collected in other aspects of this study (see Objective A). All coding has been done in C++. The data generation portion of LINKAGES is also undergoing significant revising to allow specification of "exact" initial conditions with regard to existing forest conditions. This step is necessary for the study of statewide scenarios under Objective B of this study that will utilize FIA data and auxiliary data now be collected as part of Objective B. A computer graphical front-end for the LINKAGES model has been developed. The front-end allows clearer visualization of a landscape (tree birth, death, successional processes) as predicted by the LINKAGES model. This Front-end will be used in the technology-transfer phase of this study where results are present to interested parties.

Two conferences were attended where other scientists working on global change modeling projects were gathered to discuss the "state-of-the-art". Efforts from this study were discussed and opportunities for incorporating other research groups' work (probably related to weather and nutrient cycling components of LINKAGES) into our efforts were explored.

Soil samples are collected from various aspen stands where plots are established for Objectives A and B. The samples are being analyzed for C and N to determine the relationship between soil C and N status and site productivity. The equations will be used for developing the forest growth model.

Final status report for July 1, 1993: The ecosystem model LINKAGES was refined to allow for input of field plot data. Field data were compiled in part from FIA data. Specifically, average stands were generated using FIA stands of medium density, young age, and medium to high aspen content for the NE, Central, and SE regions of Minnesota. These average stands contained information on species, dbh, and trees per acre. Individual tree information from 1/12th hectare plots is required to run LINKAGES. Average trees per acre were converted to trees per hectare and expanded into tree lists. A 1/12th hectare plot was generated by first sorting the average tree list by species and dbh, then randomly choosing the first tree of the plot from the first twelve trees of the sorted tree list, and systematically choosing every twelve tree thereafter.

Several other site-specific variables were obtained to allow for comparisons on the basis of soil and climate variations. In each region studied, three well-drained soil series common to aspen were selected, one each from course, medium, and fine texture soils. Field moisture capacity, wilting point, humus weight, and nitrogen content in the humus were calculated from the soil series information. A representative city in the region was used to draw latitude and longitude, growing season, annual precipitation, and temperature.

Simulating stand development with LINKAGES allowed for study of long term effects of initial conditions. Interestingly, in all the cases studied, mortality of aspen was extreme with little or no ingrowth. Even in circumstances when aspen represented a substantial portion of the overall stand basal area and biomass (20-100%), percent of trees representing aspen was less than 10% at the end of 100 years of simulation. At the end of the simulation period, initially high composition aspen stands were still generally higher in terms of percent biomass and basal area than low composition aspen stands in the same region with similar soils. Additionally, as soil texture became finer, aspen occupied a greater percentage of the basal area and represented a greater portion of the biomass. Regional differences were also observed. Region four showed the greatest percentage of aspen at the end of 100 years simulation.

C.6. Benefits: This modelling capability would serve as a basic tool for a wide range of ecological and silvicultural analyses important to environmental impact assessment and forest management planning. These capabilities are essential to approach possible environmental changes in the next several decades whether they be of natural or anthropogenic origin.

IV. EVALUATION

A number of nutrient cycling studies have been conducted, but questions remain for certain soil and species combinations. For the 91-93 biennium this project can be evaluated by its success in:

- assembling a quality data set for understanding nutrient cycling on the study sites
- synthesizing existing data, new data and published results into a clear picture of the soils/nutrient/atmospheric change/forest management situation for the study sites.
- developing relationships for extrapolating results to other parts of the state
- incorporating the results into a computer simulation model useful to forest managers, ecologists and other interested parties for studies of the implications of harvesting, management and climate change.

This evaluation can also be developed by comparison to similar studies being conducted in other regions for different species-site combinations. Additionally, the study should highlight Minnesota and its institutional capability and study sites as valuable scientific assets.

On a longer time scale, the project will establish the basis for an understanding of the relationships between forest ecosystem processes, forest management and atmospheric change. The extrapolative utility of the study result will be a key criteria for evaluation.

V. CONTEXT

A. This is a new project intended to assist forest management decisions. However, it will be able to draw on previous research and study sites in the state. The project would provide important information on the implications of management choices of species, regeneration technique, rotation length and utilization level. This information will provide much greater definition than what we know today. It is crucial to management for sustained long term productivity. Results would also be central to the planned generic environmental impact statement on timber harvesting. The project is assisted by several previously funded LCMR projects. This is planned as a four to eight year study, with a variety of intermediate results. If funded for the first two years, we would ask for approximately similar funding for the next biennium. The investigators are confident that they can develop support beyond the fourth year. In fact, the proposed initial funding for four years could lead to Minnesota being a lead national site for such research.

B. This work will supplement previous by adding species and site quality specifics pertinent to forests and their management in Minnesota.

C. There have been no past LCMR funds used in this area.

D. Not applicable

E. Biennial budget system program title and budget: Not available at this time.

VI. QUALIFICATIONS

A. Program manager

Dr. Alan R. Ek, Professor and Head
Department of Forest Resources
University of Minnesota, St. Paul, Minnesota

Ph.D. Forest measurements, Oregon State University, 1969.
M.S. Forestry, University of Minnesota, 1965.

Dr. Ek has experience in project management and the modelling of forest stand growth. His primary role will be as program coordinator to ensure that project components considered by co-investigators come together well and as a co-investigator under objective C in adapting the existing LINKAGES model of forest growth and nutrient cycling to meet study objectives.

B. Major cooperators/co-investigators

1. Dr. David H. Alban, Research Soil Scientist
Forestry Sciences Laboratory
USDA Forest Service, North Central Forest Experiment Station
Grand Rapids, MN

Ph.D. Forest Soils and Ecology, Washington State University, 1967.
B.S. Forest Management, University of Washington, 1964.

Dr. Alban specializes in forest soils research. His role will be liaison with the USDA Forest Service North Central Forest Experiment Station and advising on study design, notably for objective A.

2. Dr. Thomas E. Burk, Associate Professor
Department of Forest Resources
University of Minnesota, St. Paul, MN

Ph.D. Forest Biometrics, University of Minnesota, 1981.
M.S. Statistics, University of Minnesota, 1980.
M.S. Forestry, University of Minnesota, 1978.

Dr. Burk's specializes in experimental design and the modelling of tree growth. His primary roles will be in analysis and validation of model components, design of the sampling scheme for objective B and integration of existing models in objective C.

3. Dr. Terence H. Cooper, Associate Professor
Department of Soil Science
University of Minnesota, St. Paul, MN

Ph.D. Soil Science, Michigan State University, 1975.
M.S. Soil Science, Michigan State University, 1969.

Dr. Cooper's specialization is in soil morphology and classification. His primary roles will be under objective A concerning mineral weathering and under objective B in developing forest soil interpretations for study sites and a broader range of common forest soils.

4. Dr. David F. Grigal, Professor
Department of Soil Science
University of Minnesota, St. Paul, MN

Ph.D. Soil Science and Forestry, University of Minnesota, 1968.
M.S. Forestry-biostatistics, University of Minnesota, 1965.

Dr. Grigal specializes in forest ecology and soils. His primary role will be under objective A in the collection of nutrient cycling data, including weathering information and in assessing growth responses. He will also assist in study design including that for objective B.

5. Dr. John Pastor, Research Associate
Natural Resources Research Institute
University of Minnesota, Duluth, MN

Ph.D. Forestry and Soil Science, University of Wisconsin, Madison, 1980.
M.S. Soil Science, University of Wisconsin, Madison, 1977.

Dr. Pastor's specializes in forest ecology with particularly emphasis on modelling soil processes. His primary role will be under objective C in modelling nutrient and carbon cycling with the LINKAGES model and scenario development and in study design to ensure the collection of critical modelling inputs. However, he will also advise on design for objective A.

6. Dr. Donald A. Perala, Principal Silviculturist
Forestry Sciences Laboratory
USDA Forest Service, North Central Forest Experiment Station
Grand Rapids, MN

Ph.D. Forestry, University of Minnesota, 1987.
M.S. Forestry, University of Minnesota, 1963.

Dr. Perala's specializes in silvicultural research. His role will be liaison with the USDA Forest Service North Central Forest Experiment Station and advising on study design, notably for objective A.

7. Dr. Michael J. Phillips, Forest Soils Program Supervisor
Division of Forestry
Minnesota Department of Natural Resources
St. Paul, MN

Ph.D. Forest Soils, University of Canterbury, New Zealand, 1981.
M.S. Forest Soils, Oregon State University, 1976.

Dr. Phillips is a specialist in the area of forest soils. His role will be liaison with the Department of Natural Resources in the selection of study sites, advising on management data needs, and assisting in study design and interpretation of study results to the forestry community and the public. He will have a primary role in integrating study results and recommendations into ongoing and future forest management programs.

8. Dr. Edward I. Sucoff, Professor
Department of Forest Resources
University of Minnesota
St. Paul, MN

Ph.D. Plant Physiology, University of Maryland, 1960.
M.S. Forestry, University of Michigan, 1956.

Dr. Sucoff specializes in tree physiology and plant water relations. His primary role will be under objective A to help incorporate plant water relations and CO_2 and carbon dynamics into data collection, analysis and modelling. He will also lead the gradient analysis component of this objective.

9. A postdoctoral research associate and several graduate research assistants will also be hired to assist the project manager and co-investigators in project execution.

VII. REPORTING REQUIREMENTS

Semiannual status reports will be submitted not later than January 1, 1992, July 1, 1992, January 1, 1993 and a final status report by June 30, 1993.

A. Significant Problems

No significant problems have arisen to date except that we are slightly overbudget with repect to field travel expenses and sample analysis cost. This may force a reduction in the field effort and is postponing some lab analyses. The problem has been alleviated in part by matching support from related projects.

Disapproval of two more years of additional funding for this project may cause discontinuation or postponement in some long-term studies involved. The established research plots and records will be maintained as far as possible for future continuation of the studies when more funding becomes available. However, lack of funding for specific study site protection from hare and beaver damage may lead to the loss of some study plots.

1993 RESEARCH PROJECT ABSTRACT
FOR THE PERIOD ENDING JUNE 30, 1993

TITLE:	Impacts of intensified forest management and atmospheric change on nutrient cycling and tree species suitability
PROGRAM MANAGER:	Dr. Alan R. Ek
ORGANIZATION:	Department of Forest Resources, University of Minnesota
LEGAL CITATION:	M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd. 7(b)
APPROP. AMOUNT:	$220,000

STATEMENT OF OBJECTIVES
To understand forest nutrient cycling processes and tree requirements to deal effectively with the management questions concerning species-site matching, choice of rotation lengths, and appropriate levels of tree and stand utilization. Also to provide field data for modelling and estimating forest growth in Minnesota under various levels of forest management intensity and to assess implications of atmospheric change. Modelling capabilities are to be used for state-wide extrapolation of study findings to a wide range of sites. A particlular concern was to determine if Calicum removal from timber harvesting is likely to lower the productivity of aspen sites.

RESULTS
Data were collected from 65 aspen sites to investigate forest nutrients and their relationships to site productivity. Analysis of that data with respect to key study questions is described below:
1) How much new calicum is added annually from soil weathering? **Answer**: Slightly less than previously thought.
2) Does calicum and/or nitrogen availability limit aspen growth? **Answer**: There is a positive correlation of growth and such nutrient availability and we have recently determined critical levels. Fertilization studies to confirm and refine that understanding are still in progress. However, extrapolation via simulation to other than specific study sites will have to wait until more soils data is available to assess initial (start of simulation) conditions.
3) How do we tell which soils and harvesting practices or rotation lengths are limiting? **Answer**: The study provided important inputs need for our long term simulation analyses. Included are findings that show aspen productivity to be positively correlated with soil Ca. Nitrogen addition also improved aspen growth on some sites. The rates at which aspen stands store and accumulate nutrients added by atmospheric deposition and soil weathering were also determined. Further, nutrient cycling via litterfall greatly exceeded the nutrient fluxes into and out of the system in the early stages of stand development. Nutrient cycling in young aspen stands was also unexpectedly high with a corresponding increase in available nutrients. Increased soil moisture was also a major factor in favoring nutrient cycling. Soil and aspen stand data collected during the study came from a wide range of aspen sites in Minnesota and are now accessible for modelling forest growth. The ecosystem simulation model LINKAGES was also refined to facilitate long-term modelling analyses. Soil specific simulation studies of stand development and nutrient cycling are now beginning, but information from more study sites is needed. In brief, the study provided considerable data, understanding and methodological development for statewide assessment of the potentials and future of aspen stands and related soil resources.

PROJECT RESULTS USE AND DISSEMINATION
Several research papers have been prepared and more will be developed after the completion of ongoing analyses. A key reference will be: "Impacts of Intensified Forest Management ... on Nutrient Cycling of Aspen Forests ..." Staff Paper Series, Dept. of Forest Resources, Univ. of Minn. The study also contributed findings helpful to the GEIS on timber harvesting & forest management.

Detailed . ion

July 1, 1993

LCMR WORK PROGRAM 1991

I. Impacts of intensified forest management and atmospheric change on nutrient cycling and tree species suitability

Program Manager:	Alan R. Ek Forest Resources University of Minnesota St. Paul, MN 55108 612/624-3400

A. M.L. 91, Ch. 254, Art. 1, Sec.14, Subd: 7(b)	Appropriation:	$220,000
	Balance:	$0

Impacts on intensive forest management: This appropriation is to the University of Minnesota, Department of Forest Resources, to assess the role of nutrient cycling and associated management practices for sustainability of Minnesota's forest resources under scenarios of increased harvesting and atmospheric change.

B. Compatible data: Not applicable. However, standardization of measurements and recording will be a goal to facilitate wide use of the data and its use with research and other data bases such as those maintained by the Minnesota Land Management Information Center's geographic information center, the USDA Forest Service North Central Forest Experiment Station, the Great Lakes Forest Growth and Yield Cooperative, and other LCMR projects, notably those concerning old-growth forests, regeneration/management of oak forests and aspen decay models.

C. Match requirement: Not applicable.

II. NARRATIVE

Minnesota's forests will come under increasingly intensive management in the next several decades. That poses questions about the choice of forest stand rotation age that favors the sustainability and enhancement of soil and site productivity. At the same time, air quality changes, perhaps including changes in precipitation and temperature patterns, may impact fundamental plant and soil processes. Fundamental understanding of nutrient cycling processes and tree requirements is needed soon to deal effectively with the management questions concerning species-site matching, choice of rotation lengths and appropriate levels of tree and stand utilization. The question is complicated by the range of soils and ecosystems in the state and the fact that long term studies are essential to this research. Answers to the above questions have implications for understanding the dynamics of a variety of forest flora and fauna.

The proposed study has experimentation, monitoring and modelling components. However, there are important tradeoffs between these for a cost effective and penetrating project. Judicious experimentation and effective modelling will reduce the need for and cost of monitoring. Alternatively, monitoring serves as a data base for validation of the modelling. Objective A will collect data needed to refine the model chosen for use in the study. Objective C will use the data from objective A to modify and improve the model. Objective B will collect data to allow the extrapolation of model results to a wide range of sites. Objective B also sets the stage for state-wide extrapolation to be carried out in years 3-4. To the extent possible, extrapolation will be based on the results of the first two years, but some additional sampling of sites in years 3-4 will be necessary. The three objectives are described below. Specifications will be developed further and finalized in the spring of 1991.

III. OBJECTIVES

A. ESTIMATE SITE SPECIFIC IMPACTS OF TIMBER HARVESTING ON FOREST SOILS AND NUTRIENT CYCLING. (leaders: Grigal, Alban, Perala, Pastor, Sucoff)

A.1. Narrative: Intensive investigations of nutrient use efficiency are proposed for sites of different elemental capital. Investigations will be concentrated on aspen of two ages on three types of soils. Aspen was selected because it is the major species harvested in Minnesota and it is known to be nutrient demanding. Observations will include monitoring of tree growth, stand water balance, atmospheric deposition of nutrients, soil nutrient status, litter dynamics and biomass over a four to eight year period. Both undisturbed and fertilized plots will be examined. The emphasis will be on improving our understanding of nitrogen, calcium and carbon cycling and how these influence the response to harvest and potential atmospheric change

This study component is designed to collect sufficient data to refine the LINKAGES model discussed in part C. In particular we seek data to add a meaningful calcium availability module and a calcium response module to LINKAGES. We will stress the use of data from pre-existing USDA Forest Service study sites and add a poor site to complete the study matrix of sites. We would monitor fluxes in both young and mature stands, selecting those near weather stations. Additionally, fertilizer or stable isotopes might be added to some sites to allow estimation of annual turnovers, particularly of calcium. However, such isotope studies would not begin until year three or beyond, as the technique needs further development. The general hypotheses motivating the study design are that 1) repeated harvests have the potential to lower productivity through the depletion of calcium or nitrogen and 2) soil differences have a major predictable impact on sustainability. Specifically, a nutrient demanding tree species like aspen may be more difficult to manage on a sustainable basis on nutrient poor sites. The key is to quantify tree requirements over time and determine the ability of soils to supply these needs.

A.2. Procedures: An important step in the success of this study objective is to locate aspen on a site that will fill the most serious data gaps given existing installations. That choice will be a poor site where nutrients are expected to be limiting. Where possible, subject stands of other species will be located nearby for possible extension of the study to facilitate comparisons among species. Additional species including red pine and oak would be added, but only if more funds were available. As it stands, we would rely on cooperating studies by the USDA Forest Service for aspen, white spruce, paper birch and mixed aspen/ hardwood stands. The table below is suggestive of the study design:

Cover type/age class	Soil		
	Poor	Light	Heavy
Aspen young	x	x[c]	x[c]
mature	x	x[c]	x[c]

[c]Existing cooperator sites (USDA Forest Service, Cloquet and Pike Bay, Minnesota)

The poor aspen site (poor in N and Ca) provided by this proposal will add considerable leverage to the inference capability provided by the existing sites. Data collection efforts on these six stands are referred to as the intensive study.

Each cell in the chart above, i.e., each soil and age combination, would involve study sites of a minimum of 2 hectares in size upon which we would collect and examine data as described in the next paragraph. In effect, we would seek two locations (landform x soil combinations) that have stands of both ages in close proximity. The young stands, in effect, would describe site and stand conditions and development following harvesting. This would be a stand harvested in the last five years. The mature stand would be chosen to approximate pre harvest conditions and processes. Candidate sites are available within 75 miles of the Cloquet Forestry Center and will be located in the spring of 1991.

Data to be considered for collection would include:

- Site and stand history
- Aerial photography (historical and new large scale for crown mapping)
- Landform/physiographic condition
- Soils and soil mapping unit data
- Climatological data including solar radiation (from nearby weather station)
- Water balance (evapo-transpiration, leaching, runoff, etc.
- Overstory and understory vegetation monitoring plots (every other year beginning in 1991)
- Biomass and tissue nutrient content
- Atmospheric deposition of nutrients
- Litterfall
- Litter decomposition
- Fine root biomass
- Effective rooting depth
- Soil physical properties
- Soil chemistry by major horizon (Ca,Mg,N,P,K and C every fourth year beginning in 1991)
- Soil solution chemistry (monthly)
- Total analysis of soil (soil mineralogy)

In general, study procedures would follow those described by Alban and Perala (1989) for ongoing studies of nutrient and carbon dynamics at several sites in the Lakes States. Using similar procedures would ensure compatibility of various study data and broaden the base for inference. The intensive study will provide physiological justification for modelling direction and knowledge of soil changes after harvesting, ecosystem storage pools, annual dynamics of the systems considered and how the sites (3) differ in storage and dynamics. However, there is a need to focus the set of variables and to assess the most cost effective way to observe them. Thus detailed procedure specification is an important early portion of the study. Some possible exceptions and additions to previous procedure are described below.

The overstory monitoring plots (four @ 0.05 hectares for each cell in the above table) for observation of trees greater than 1.3 m in height would include species, diameter at breast height (dbh), biomass, leaf area, etc. The understory vegetation monitoring plots (at least five @ $4m^2$) would be situated within the overstory plot for observation of species, density and biomass of small trees, shrubs and herbaceous vegetation. Aspen clones will be identified by morphology and phenology.

Additional information will be collected on soils with to quantify a) mineral weathering component of nutrient availability (leaders: Grigal, Cooper) and b) growth responses (leaders: Grigal, Sucoff). For nutrient availability, we will model and measure nutrient fluxes at the effective rooting zone. Lysimeter solution chemistry will be linked with hydrologic flux. We will determine N availability by measuring its mineralization rate with buried resin bags and/or soil cores. This rate is highly correlated with productivity. For calcium, we will collect data needed to refine and use pre-existing models of weathering rates of soil minerals. Those models have been developed in Scandinavia to assess the impacts of acid deposition on forests. Needed data include soil mineral composition, surface area, and soil solution chemistry. The proposed intensive site on a poor soil, the pre-existing USDA Forest Service sites and supplemental sites included under the gradient study described below will be sampled to provide the data to allow parameterization of the model. After parameterization, a simplified form of the model will be integrated into LINKAGES. This effort to quantify nutrient availability is designated the weathering study.

The responses of aspen to nitrogen and calcium singly and in combination will be determined in sufficient detail to be incorporated into the LINKAGES model. These responses will be determined in two ways: a fertilizer experiment and a gradient analysis of aspen stands across the region. The fertilizer and the gradient study will then be integrated to provide the response equations demanded by the model.

The need for developing response functions is illustrated by the paradox as to which nutrient limits growth of aspen. Fertilizer trials have always indicated nitrogen limitation. On the other hand, nutrient budget calculations that compare nutrient removals in harvested biomass with reserves in soil often show that calcium may become limiting. Consequently, data will be collected and analyzed using a combination of traditional approaches and recent physiologic understanding of calcium function and transport.

The fertilizer study (leader: Sucoff) will be conducted on two sites deficient in both nitrogen and calcium and on two sites with moderate levels of nitrogen and calcium. Two of these installations will be located on the intensive study sites, notably the poor and light soils. The other two will be installed on soils equivalent to these sites. Small areas will be treated with a range of calcium and nitrogen levels and ratios. For cost effectiveness, the fertilizer treatments will be applied to individual trees. The responses will likewise be measured on individual trees, with each treatment replicated 10 to 15 times on each site. On each single tree plot the following variables will be measured:

- Tissue (leaves, bark, wood) Ca, N and other essential elements (pretreatment and annually, with several trees measured both in spring and late summer)
- Growth response to treatment

On each site involved, the following variables will be measured:

- Soil solution N, Ca (periodic)
- N with resin bags (periodic)
- Physical properties of the soil
- Chemical properties of the soil
- Climatological variables

The gradient study (leader: Grigal, Sucoff) will include the study sites in objective A and a number of the sites identified under objective B. The intent is to examine aspen stands geographically situated across Minnesota and the region. The purpose is to determine how productivity of aspen stands is associated with calcium and nitrogen levels in tree leaves, bark, wood and soil. Although a range of upland sites will be sampled, the emphasis will be on sites which are of likely to be low in calcium and nitrogen and on sites which are of low productivity. On each site the following variables will be measured:

- Tissue (leaves, bark, wood) Ca, N and other essential elements (sampled in late summer)
- A measure of soil Ca and N which will correspond to available Ca and N
- Tree biomass and age
- Annual climate during years since establishment

The data from the fertilizer and gradient studies, like the intensive study, will be analyzed to develop response curves and the identification of deficient elements.

In important exception to past procedure, we will emphasize the use of sampling and existing data including relationships (equations) from the literature to reduce costs and allow focus on the key processes (nutrient storage and availability) we seek to understand. Thus sampling and the construction of relationships between easily measured variables and more difficult to assess ones will be utilized extensively. Also, overstory biomass estimation will rely heavily on biomass/tree dimension relationships in the literature rather than destructive sampling.

There is already information on direct nutrient and carbon removals from harvesting and we will not duplicate that work. Throughfall and stemflow are other variables where literature values or substitution of soil solution and litter sampling will be cost effective.

References on background and procedure are:

Alban, D. H. 1982. Effects of nutrient accumulation by aspen, spruce and pine on soil properties. Soil Sci. Soc. Am. J. 46 (4): 853-861.

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. Forest Res. 8:290-299.

Alban, D. H. and D. A. Perala. 1990. Ecosystem carbon following aspen harvesting in the upper Great Lakes. In: Aspen Symposium Proc. '89. USDA Forest Service Gen. Tech. Rep. NC-140. pp: 123-131.

Binkley, D. 1984. Ion exchange resin bags: factors affecting estimates of nitrogen availability. Soil Sci. Soc. Am. J. 47:1050-1052.

Binkley, D., J. D. Aber, J. Pastor and K. Nadelhoffer. 1986. Nitrogen availability in some Wisconsin forests: Comparisons of resin bags and on-site incubators. Biol. and Fert. of Soils 2:77-82.

Boyle, J. R. and A. R. Ek. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. Forest Res. 2:407-412.

Eno, C. F. 1960. Nitrate production in the field by incubating the soil in polyethylene bags. Soil Soc. Soc. Am. Proc. 24:277-299.

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 U.S. forests. Environ. Mgmt. 13(5):593-601.

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. Environmental Quality. 19:97-104.

Minnesota Department of Natural Resources. 1989. An evaluation of the potential for calcium depletion in aspen sites in Minnesota. Division of Forestry, Forest Soils Unit. 12p.

Pastor, J., J. D. Aber, C. A. McClaugherty and J. M. Melillo. 1984. Above ground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin, Ecology 65:256-268.

Pastor, J. and J. G. Bockheim. 1984. Distribution and cycling of nutrients in aspen-mixed hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65:339-353.

Perala, D. A. and A. H. Alban. 1982. Biomass, nutrient distribution, and litterfall in *Populus, Pinus and Picea* stands on two different soils in Minnesota. Plant Soil 64:177-192.

Ruark, G. A. and J. C. Bockheim. 1987. Biomass, net primary production, and nutrient distribution for an age sequence of *Populus tremuloides* ecosystems. Can. J. Forest Res. 18:433-443.

Silkworth, D. R. and D. F. Grigal. 1982. Determining and evaluating nutrient losses following whole tree harvesting. Soil Sci. Soc. Am. J. 46:626-631.

Summers, K., S. Gherini, R. Munson, R. Hudson, D. Johnson, and L. Pitelka. 1990. The IFS nutrient cycling model: overview and application. TetraTech, Lafayette, CA. Unpublished mimeo.
Sverdrup, H. and P. Warfvinge. 1990. Modelling chemical weathering rates of primary silicate minerals: Consistency between observed field rates and model predictions. Unpublished mimeo.
Timmer, V. R. and E. L. Stone. 1978. Comparative foliar analysis of young balsam fir fertilized with NPK and lime. Soil Science Soc. Amer. J. 42:125-130.
Van Cleve, K. and L. K. Oliver. 1982. Growth response of postfire quaking aspen to N, P and K fertilization. Can. J. Forest Res. 6:145-152.
Walters, D.K., and A.R. Ek. 1989. General guidelines for the installation and measurement of permanent forest inventory plots. Univ. Minnesota Dept. Forest Resources, Great Lakes Forest Growth and Yield Cooperative Pub. No. 1. 6p. plus appendix.
White, E. H. 1974. Whole-tree harvesting depletes soil nutrients. Can. J. Forest Res. 4:530-535.

A.3. Budget:

	LCMR funds	Matching funds
Amount Budgeted:	$160,000	$0
Balance:	$0	$0

A.4. Timeline for Products/Tasks

```
                                   Jan91  Jul91  Jan92  Jun92  Jan93  Jun93

Literature review and specification
     of detailed procedure -------------|
Study site identification  -------------|
Observation of initial conditions   -------|
Monitoring apparatus installation   -----|
Field data collection      ------------------------------------------------------|...
     -intensive study
     -weathering study
     -fertilizer study
     -gradient study
Laboratory analysis          --------------------------------------------------|...
Synthesis                                -----------------|   -------------|...
```

A.5. Status:

Final status report for July 1, 1993:

1. Gradient study

The gradient study examined the relationship between soil Ca levels and aspen productivity. Thirty stands were sampled between Brule, Wisconsin and Bemidji, Minnesota. A number of candidate stands were identified by various public forest management agencies. Stands were chosen for sampling that met the following criteria; (1) Predominantly quaking aspen (*Populus tremuloides*), aspen being greater than half of the stand basal area, (2) Aspen greater than 30 years old, (3) Aspen stands free from obvious insect and disease damage.

Data and samples were collected at 3 randomly located points within each stand. Diameter at breast height (dbh) and species of all "in" trees (based on 10 BAF variable radius plot) were measured and recorded. Age and height of the closest dominant or codominant aspen tree to point center were measured. Samples of the bark and the outer 1 cm of wood were collected from three sides of the sample tree. These tissue samples were extracted with a 5-cm diameter hole saw. Soil samples were collected from 3 locations around the sample tree (1.5 m from the base of the tree at azimuths of 45, 135, and 225°). Forest floor samples were collected by forcing a 12.3-cm diameter steel ring through the forest floor and collecting all of the forest floor material inside the ring. Samples of the upper 25 cm of the mineral soils were collected with a soil probe directly beneath where the forest floor had been sampled. The three forest floor and the three mineral soil samples collected at each point were composited in the field (yielding one forest floor sample and one mineral soil sample for each point). At one point in each stand, soils were examined to a depth of 1.5 m and tested for the presence of $CaCO_3$ with 10% HCl. Soil samples were analyzed for exchangeable Ca (ICP analysis of solutions extracted with 1*M* NH_4NO_3) and loss-on-ignition (ashed at 450°C). Calcium concentration in the wood and bark samples was determined by ashing the samples at 450 °C and then digesting the ash in concentrated HCl. The calcium concentration of the resulting solution was analyzed with ICP.

Forest floor Ca was estimated from the results of the ICP analyses. These were converted to an areal basis using an expansion factor based on the mass and known area sampled. Exchangeable calcium in upper 25 cm of mineral soil was also estimated from the results of the ICP analyses and converted to an areal basis using estimated soil bulk density. Relative stocking index (RSI), an index of relative stocking based on the relationship between average tree diameter and stand density, was calculated for each stand. A norm or average relationship between tree diameter and stand density has been established for aspen stands in Minnesota using FIA data (Bill Berguson 1993, NRRI, personal communication). Site index was estimated from age and height data using equations developed by Lundgren and Dolid (1970). Stand biomass was estimated using Alemdag's (1983, 1984) biomass equations which estimate above-ground biomass from tree dbh and height. Each variable was estimated separately for each of the three sample points in each stand. Average value then was calculated for each variable in each stand, and these average values were used in our data analyses. Three stands were eliminated from the analyses because of outliers, two were understocked and the third had high wood calcium levels. Relationships between variables of interest were evaluated with correlation analysis and simple linear regression using PC SAS ver. 6.04 (SAS Institute, 1989).

Results showed that sampled stands did fall along a considerable gradient in soil calcium levels (see Table 1). Total exchangeable Ca in the forest floor and upper

Table 1. Descriptive statistics of soil and tissue calcium data and stand productivity indices.

Variable	Mean	Std. dev.	Minimum	Maximum
Exch. soil Ca (kg/ha):				
Forest floor	179	189	21	897
0 to 25 cm	2210	1521	678	6608
Combined (soil)	2390	1622	828	7505
Tissue Ca (mg/g):				
Bark	14.0	2.2	10.5	19.2
Wood	1.1	0.2	0.9	1.5
Forest productivity:				
RSI	1.1	0.3	0.7	1.8
Site index (m)	22.8	2.2	16.4	28.2
Biomass (Mg/ha)	140.1	32.3	68.6	199.6

25 cm of the mineral soil ranged from about 800 to over 7500 kg/ha, with most of this Ca contained in the mineral soil. There also was considerable variation in tissue Ca levels and stand productivity.

A primary concern of this study was to investigate relationships between soil Ca levels and forest productivity. Two separate indices of site quality, RSI and site index, were evaluated. Also considered was stand biomass, which may be a suitable surrogate for productivity in stands that are at or near rotation age. There were no significant relationships between site index and other variables of interest (Table 2), suggesting that site index may not be a useful indicator of site quality in these stands. Similar results have been reported for other studies involving aspen in the upper Great Lakes (Bates *et al.*, 1990; Esu and Grigal, 1979). The data in this study indicate that RSI may be a better estimator of site quality in the stands. There was a significant and positive correlation between RSI and stand biomass (Table 2).

Overall, There was a significant correlation between exchangeable soil Ca and productivity. While this relationship appears valid, it is not clear that productivity in these stands is directly a function of Ca levels in the soil. Other properties may also be correlated with soil Ca, including the availability of other nutrients and of soil water. However, there is some evidence that Ca levels in tree tissues may be correlated with soil Ca. Calcium concentration in the outer 1 cm of wood was positively correlated with exchangeable soil Ca. Wood Ca levels were weakly related to productivity, with the strongest relationship observed between wood Ca and stand biomass. These data may indicate that increased Ca availability in the soil can lead to increased Ca uptake and accumulation in wood tissues which can ultimately be related to greater productivity. There was not any apparent relationship between bark Ca levels and either soil Ca or stand productivity.

Table 2. Correlation coefficients between selected variables and p-values (in parentheses) for the hypothesis that the correlation coefficient = 0.

	SI	Biomass	FF Ca	0-25 Ca	Soil Ca	Wood Ca	Bark Ca
RSI	-0.033 (0.87)	0.505 (0.01)	0.293 (0.14)	0.497 (0.01)	0.500 (0.01)	0.245 (0.22)	-0.317 (0.11)
SI		0.184 (0.36)	-0.074 (0.72)	-0.015 (0.94)	-0.023 (0.91)	-0.008 (0.97)	0.047 (0.82)
Biomass			0.309 (0.12)	0.408 (0.03)	0.418 (0.03)	0.337 (0.09)	-0.083 (0.68)
FF Ca				0.486 (0.01)	0.572 (0.01)	0.100 (0.62)	0.040 (0.84)
0-25 Ca					0.994 (0.00)	0.462 (0.02)	-0.129 (0.52)
Total Ca						0.445 (0.02)	-0.11 (0.56)
Wood Ca							0.445 (0.02)

The relationships between soil Ca and site productivity (RSI) and between soil Ca and wood Ca were tested with regression equations:

$$\text{RSI} = 0.9302 + 7.864 \times 10^{5} \times \text{soil Ca} \quad (\text{adj. } R^2 = 0.25) \qquad (1)$$

$$\text{wood Ca} = -0.20252 + 0.17095 \times \ln(\text{soil Ca}) \quad (\text{adj. } R^2 = 0.28) \qquad (2)$$

where soil Ca is in kg ha^{-1} and wood Ca in mg g^{-1}. These reflect the general trends that was identified above; (1) a significant, positive correlation between soil Ca levels and wood Ca concentrations, (2) a significant, positive correlation between soil Ca and productivity as estimated by RSI, and (3) weak evidence of a correlation between wood Ca levels and productivity.

Literature cited

Alemdag, I. S. 1983. Mass equations and merchantability factors for Ontario softwoods. Can. For. Serv. Inf. Rep. PI-X-23.

Alemdag, I. S. 1984. Total tree and merchantable stem biomass equations for Ontario hardwoods. Can. For. Serv. Inf. Rep. PI-X-46.

Bates, P. C., P. C. Robert, and C.R. Blinn. 1992. Overlaying soil and timber inventories to assess aspen productivity in northern Minnesota. Soil Sci. Soc. Am. J. 56:295-301.

Esu, I. E. and D. F. Grigal. 1979. Productivity of quaking aspen (*Populus tremuloides* Michx.) as related soil mapping units in northern Minnesota. Soil Sci. Soc. Am. J. 3:1189-1192.

Lundgren, A.L., and W.A. Dolid. 1970. Biological growth functions describe published site index curves for he Lake States timber species. USDA Forest Service Research Paper NC-36.

SAS Institute, Inc. 1989. SAS/STAT user's guide. Version 6, 4th edition. Volume 1. SAS Institute, Cary, NC.

2. Weathering study

Soils were collected from the Cloquet Experimental Forest (University of Minnesota) in northeastern Minnesota, the Pike Bay Experimental Forest (Chippewa National Forest) in north central Minnesota, and on the Brule River State Forest in northwestern Wisconsin. The soils differ greatly among the sites. All soils are derived from Wisconsinan age glaciation processes. The two sites at Cloquet have sandy outwash parent material from the Superior Lobe (Omega and Cloquet series, Spodic Udipsamment and Typic Udipsamment, respectively). At Pike Bay the site is a relatively dense glacial till from the Des Moines Lobe (Warba series, Glossic Eutroboralf). One site at Brule is a clay glacio-lacustrine till (Ontonagon series, Glossic Eutroboralf) while the other is a sandy to gravelly outwash deposit from the Superior Lobe (Omega series, Spodic Udipsamment). The Ontonagon and Warba sites are calcareous in the B horizon while the three outwash sites are acid throughout. The two Omega sites were initially chosen as duplicates, but due to their differences the soil from the Brule River State Forest will henceforth be called Solon Springs in reference to the proximity of that municipality. All sites are dominated by mature aspen (*Populus tremuloides* Michx. and *Populus grandidentata* Michx.). Time since glaciation was estimated to be 11,600 BP (Teller, 1987) for all soils other than the Ontonagon soil. The Ontonagon soil is located approximately 2.5 km from Lake Superior. This area was presumably in the basin of proglacial Lake Duluth which drained ~ 9500 BP (Teller, 1987).

The climate of the study area is humid temperate, with mean annual temperature of ranging from 3°C at the Warba site to 4°C at the Ontonagon site (U.S. Department of Commerce, 1992). The mean annual precipitation ranges from 66 cm at the Warba site to 79 cm at the Solon Springs site (U.S. Department of Commerce, 1992).

General physical and chemical properties of the soils were determined for the five sites. Particle size analysis was determined by both pipet and hydrometer methods (Gee and Bauder, 1986). Field bulk density was measured by the excavation method (Blake and Hartge, 1986), soil pH with a portable flat electrode, and loss on ignition (LOI) by ashing overnight at 450°C. Organic carbon (OC) and cation exchange capacity (CEC) was predicted from linear regression equations:

$$\%OC = 0.55(LOI) - 0.11 \quad (n = 168,\ R^2 = 0.99) \qquad (3)$$

$$CEC = -2.14 + 0.31(\%\ clay) + 0.90(LOI) + 0.01e^{(pH\ H2O)} \qquad (4)$$
$$(N = 167,\ R^2 = 0.88)$$

$$CEC = -2.57 + 0.36(\%\ clay) + 0.05(\%\ silt) + 0.93(LOI) + 0.005e^{(pH\ H2O)} \qquad (5)$$
$$(n = 332,\ R^2 = 0.87)$$

where CEC is in $cmol_c\ kg^{-1}$. Elemental analysis of the silt fraction was done by a 711F energy dispersive x-ray microprobe (EDAX) coupled to a scanning electron microscope (SEM).

Four methods used to estimate cation release rates were compared in this study. Soil solution (FC70) method measures the flux of cations in the soil solution leaving the root zone. The batch method involves stirring and shaking of the soil and extracting cations with Sr and Rb solutions. Mineralogical method estimates depletion of primary minerals and elements in soils since the last glaciation. Cation release rates were also estimated with a computer model PROFILE. Variability among estimated cation release rates, even for an individual soil, was high. This variability was due to differences among methods, the method of estimation, and the assumptions inherent to the methods. In an ideal world, all methods used to estimate present cation release rates would converge on the same rate. Individual methods, however, have both positives and negatives concerning the ease of estimation and validity of results.

The four methods used here differ in degree of uncertainty. The FC70 method is fraught with assumptions that are probably not valid in all cases. Although the FC70 method was easy to apply, variability among results was high. Because of the number and kinds of assumptions necessary to calculate a weathering rate, the FC70 method was the least accurate of the methods used in this study. The assumptions used in the batch method are somewhat less tenuous than those used in the FC70 method, but the effort is greater. The uniqueness of the assumptions used in the batch study infer unknown or unexplored levels of uncertainty. Nonetheless, weathering rates calculated from the batch method were more accurate than those determined with the FC70 method. The effort necessary to run the PROFILE model was greater than for all other methods. The output of the model, only the sum of cations, was the least useful result when compared to those from other methods. Many assumptions are associated with the mineralogical method, but the validity of those assumptions are greater than with the assumptions involved in the FC70 and batch methods.

Log transformed means and variances were used to calculate the bias-corrected geometric mean (BCGM) and associated 95% confidence intervals (Table 3) (Gilbert, 1987; Parkin and Robinson, 1993). The BCGM minimizes the effect of extremely high estimates, which may be erroneous. This is especially true in the case of FC70 cation release rates for calcareous soils (Warba and Ontonagon soils), present linear rates of K release for all soils (mineralogical study), and K release for outwash soils (Omega, Cloquet, and Solon Springs soils) in the batch study. Because of the variability among methods, the BCGM and associated 95% confidence intervals are believed to be the best estimates of the actual, natural cation release rates from weathering in these soils.

Table 3. Bias-corrected geometric mean cation release rates from weathering (eq ha^{-1} yr^{-1}) for five Upper Great Lakes soils, based on variety of techniques, and associated 95% confidence intervals.

Element	Omega	Cloquet	Solon Springs	Warba	Ontonagon
Ca	150 (100-240)	120 (70-130)	80 (40-170)	170 (80-420)	190 (80-500)
Mg	100 (70-150)	100 (70-140)	80 (40-170)	60 (30-150)	150 (50-560)
K	50 (10-200)	50 (20-120)	20 (10-60)	30 (10-110)	20 (10-40)
Ca+Mg+K	300 (190-500)	310 (210-470)	160 (80-330)	270 (140-590)	480 (230-1200)

Literature cited

Blake, G. R. and K. H. Hartge. 1986. Bulk Density. pp. 363-375. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. Soil Sci. Soc. Am., Madison, WI.

Gee, G. W. and J. W. Bauder. 1986. Particle size analysis. pp. 383-409. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. Soil Sci. Soc. Am., Madison, WI.

Gilbert, R. O. 1987. Statistical methods for environmental pollution monitoring. Van Nostrand Reinhold Co., New York.

Parkin, T. B. and J. A. Robinson. 1993. Statistically evaluation of median estimators for lognormally distributed variables. Soil Sci Soc Am J 57:317-323.

Teller, J. T. 1987. Proglacial lakes and the southern margin of the Laurentide ice sheet. pp. 39-70. *In* W. F. Ruddiman and H. E. Wright (eds.) North America and adjacent oceans during the last glaciation. Geological Society of America, Inc.

U.S. Department of Commerce. 1992. Monthly station normals of temperature, precipitation, and heating and cooling degree days, 1961-1990. Eds. J.R. Owenby and D.S. Ezell. NOAA, NCDC, Asheville, North Carolina.

3. Intensive study

The main objective of this study was to investigate timber harvesting impacts on distribution, cycling, and availability of nutrients in aspen forests at three different stand ages. Study sites are located at Cloquet Forestry Center of University of Minnesota in Carlton County, Minnesota. Research plots were established exclusively on the Omega soil series (mixed, frigid, Spodic Udipsamments). The soil is 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 is mainly red, white, and jack pine; spruce-fir; and aspen-birch. One-third of this area is predominantly covered with lowland 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 that had aspen over 60 percent of species composition.

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

Precipitation was collected from three open areas in Cloquet Forestry Center. A polyethylene bottle with a 20.3-cm polyethylene funnel fitted with fiberglass net was placed in each area. Rainfall and snowfall were collected separately every 14 days in 1992. Dry deposition was estimated from wet to dry deposition ratios (W:D) of N 1:1, P 1:1, K 1:1.567, Ca 1:1.295, and Mg 1:0.77, which were obtained from low elevation forests in the United States (Johnson and Lindberg, 1992).

Vegetation was stratified into three layers: tree (>2.5 cm dbh), shrub (<2.5 cm dbh), and herbaceous ground cover. Tree dbh was measured from the 0.05 ha vegetation plots in November 1991 and November 1992. Tree biomass was estimated using measured dbh and biomass equations developed by Perala and Alban (in press). Shrub base diameter at 15 cm aboveground was measured in August 1991. The base diameter was used to estimate shrub biomass using biomass equations developed by Perala and Alban (in tress). Herb samples were collected from from the 1 x 0.5 m plots in July 1991. Plant leaf and woody tissue samples were collected in August 1991. All plant samples were oven-dried at 65°C for 48 hours and analyzed for nutrients with ICP.

Litterfall was collected using four 1 x 1 m square traps in each plot, each with a fiberglass net at the bottom. The traps were emptied biweekly in fall and bimonthly in other seasons in 1992. O horizon biomass samples were collected from four locations in each plot in October 1991 and October 1992. All litter samples were dried at 65°C for 48 hours and analyzed for nutrients with ICP. Fresh leaf litter was collected in October 1991 and air-dried for one week. Air-dried fresh leaf litter was placed in 20 x 25 cm litterbags made of fiberglass net with a mesh size of 1 mm. The litterbags were buried in O_e horizon and collected after 6, 9, 12, and 18 months. Collected litterbags were oven-dried at 65°C for 48 hours and dry weight of the litter was measured. The litterbag samples were analyzed for organic carbon with a LECO carbon analyzer and for nutrients using the same methods used for litter samples.

A soil profile description was made from a soil pit in each plot. Soil samples were collected from all the horizons and analyzed for soil physical and chemical properties. Soil N mineralization was measured by *in situ* incubation of an intact soil core in a PVC tube (Raison *et al.*, 1987; Adams and Attiwill, 1986; Rapp *et al.*, 1979). Soil was incubated aerobically at monthly intervals over a 6 month period from May to November 1992. After a one month incubation period, the upper 15 cm soil was collected and analyzed for mineral-N with a Wescan ammonia analyzer. Nitrogen mineralization was determined from mineral nitrogen at the beginning and the end of the incubation period. Denitrification activity was measured with intact soil cores collected by PVC soil corer (30 cm x 3.8 cm) and with an acetylene block method (Myrold, 1988; Burton and Beauchamp, 1984; Robertson and Tiedje, 1984). Soil cores were collected from five random locations in each plot and the activity was measured at 3-week intervals over a 6 month period from May to October 1992. Nitrogen availability index was measured using anaerobic incubation of soil (Keeney, 1982).

Soil solution was collected from ceramic-cup lysimeters during May to October 1992 (Hansen and Harris, 1975; Shephard and Mitchell, 1991; Wagner, 1962). Lysimeters were installed at 0.5 m and 1 m below soil surface at three random locations in each plot. Soil solution was collected after applying 50 kPa tension for two weeks. Most of the applied tension was maintained during the two-week period unless the lysimeters were disturbed by wildlife. Collected soil solution samples were stored frozen until they were analyzed for nutrients by ICP.
To determine nutrient outputs, nutrient concentrations were coupled with estimates of soil water flux. Evapotranspiration was estimated by applying monthly precipitation and mean monthly temperature to a computer program developed by Black (1966) (Thornthwaite and Mather, 1957). Pan evaporation data collected from the weather station at Cloquet Forestry Center were then compared with the estimation.

Total organic matter (OM) in the vegetation of aspen stands increased more than 4 times during the period from stand age 10 years to 40 years (Table 4). The relative amount of OM in the components of above ground portions of trees followed the order: bole wood > bole bark > branches > foliage for all stand ages. Shrubs and herbs contributed less than 3 percent of the system OM. Forest floor OM was approximately 30 percent of soil OM and the ratio tended to increase as the stands matured. Forest floor mass was not different between stand ages, which was probably due to no site preparation and the logging slash left on young stands. Soil OM remained unchanged throughout the stand ages. The results indicate that the forest ecosystem doubled system OM during the 30-year period.
The amount of nutrients in the vegetation increased as stand age increased following the same pattern as in vegetation OM (Table 4). Total nutrient order in aspen trees was Ca > N > K > Mg > P. Nutrients were generally distributed equally in the tree components of branches, bole bark, bole wood, and roots, except for in foliage. 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). In the present study, aspen stands seemed to accumulate proportionally greater amount of nutrients in branches as they grew older, this was due to the invasion of other tree species carrying greater biomass on branches. Nitrogen and Ca were the most abundant nutrients accumulated in shrubs. Shrub nutrient content did not change throughout all stand ages. In herbs, K was significantly higher than other nutrients. Shrubs and herbs contributed less than 3 percent of the system nutrients.

Table 4. Organic matter (t/ha) and nutrients (kg/ha) in vegetation and soil in aspen stands at three different ages

	Overstory						Understory			Soil			System total
	Foliage	Branch	Bark	Wood	Root	Total	Foliage	Stems	Herbs	O	A	B	
Organic Matter													
Mature	4.5	18.7	23.0	93.1	27.8	167.1	0.7	2.5	0.5	19.4	30.9	32.4	234.1
Mid-age	2.5	9.6	13.3	57.3	17.4	100.1	0.9	2.9	0.7	18.7	30.0	29.0	163.6
Young	1.2	1.4	4.3	17.4	12.4	36.8	0.8	2.2	0.5	19.4	34.4	35.4	110.1
Total N													
Mature	110.7	180.0	76.6	90.2	97.4	554.9	12.4	22.4	9.5	255.6	880.8	1150.7	2886.3
Mid-age	57.6	89.7	45.4	52.3	62.5	307.5	16.3	25.1	12.3	222.4	1029.2	1115.9	2728.7
Young	28.7	12.0	34.7	12.9	44.8	133.0	14.1	18.4	10.0	377.7	1449.2	1093.6	3098.0
Total P													
Mature	7.9	28.8	10.6	17.0	25.1	89.3	1.4	2.0	1.4	24.1	288.0	1495.2	1901.5
Mid-age	4.6	13.2	7.4	12.7	15.6	53.4	1.7	2.2	1.9	25.4	370.9	1884.1	2339.6
Young	2.6	1.6	4.7	3.2	11.2	23.3	1.5	1.7	1.6	29.1	504.5	1822.8	2384.5
K													
Mature	32.3	84.1	59.8	118.5	105.8	400.6	6.3	6.6	15.2	45.1	3424.0	5313.9	9211.7
Mid-age	18.1	42.7	46.1	65.5	67.7	240.0	7.6	7.0	18.7	52.2	2958.0	8910.8	12194.2
Young	12.5	6.0	26.2	12.4	48.5	105.5	6.5	6.2	17.2	44.4	1197.4	5977.7	7354.8
Ca													
Mature	50.2	233.8	317.3	110.4	261.7	973.5	7.0	26.7	5.3	367.0	3040.0	8228.7	12648.2
Mid-age	32.2	124.2	168.1	98.3	217.1	639.8	8.4	24.9	5.3	368.1	2464.6	13762.1	17273.2
Young	9.1	16.1	73.4	22.2	155.6	276.3	7.3	18.3	5.4	359.0	3671.9	10785.8	15123.9
Mg													
Mature	11.0	25.9	16.4	16.6	27.8	97.7	1.7	1.9	1.5	40.8	1134.4	12547.3	13825.3
Mid-age	5.7	11.1	10.3	11.2	19.1	57.3	2.1	1.8	1.6	36.9	1860.8	15933.2	17893.7
Young	2.9	1.5	5.7	4.1	13.7	27.8	1.8	1.4	1.4	38.3	1370.8	13030.4	14471.9

Calcium was the most abundant nutrient in the forest floor and N was next to Ca (Table 4). Unlike other nutrients which remained the 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 the forest floor than in vegetation, with an exception being K. Potassium was much higher in vegetation than in the forest floor in young stands. Nutrient content in the soil was substantial even if the soil has shallow A horizon (6.2 cm depth) and sandy soil texture. Nutrients in A horizon was approximately 50 percent for N, 30 percent for K, 20 percent for P and Ca, and 10 percent for Mg of soil nutrients within upper 50 cm soil. Total nutrient order in soil was Mg > C > K > N > P.

Calcium was the most abundant element measured in wet deposition with 10.7 kg ha^{-1} being added to the study sites in 1992. Other nutrients added to the site were in the order of total N, K, Mg, and total P. Precipitation nutrient concentrations 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 2 to 3 times higher than the values estimated in the past. The difference in nutrient input estimates occurred by adding dry deposition. 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 becomes twice of that from wet deposition.

Potential evapotranspiration (PET), calculated with a computer program developed by Black (1966), was 61.4 cm yr^{-1}. Actual evapotranspiration (AET) estimation was 52.1 cm yr^{-1}, which was comparable to the 52 cm yr^{-1} AET measured from an aspen stands on a Spodosol in Russia (Molchanov, 1963). Pan evaporation measured at the Cloquet Forestry Center was 37.6 cm yr^{-1}. Nutrient leaching losses were relatively low in all study sites. Calcium was the most abundant nutrient in leaching solution. Cation leaching losses tended to increase in young stands. Atmospheric deposition of nutrients exceeded leaching loss in 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).

Nutrient cycling via litterfall greatly exceeded the nutrient fluxes into and out of the system (Table 5). Annual litterfall was greater in older stands. However, nutrient return by litterfall were not significantly different between different stand ages because of high nutrient contents in young aspen leaf litter. Net accumulation of nutrients from atmospheric deposition was accounted for by the net annual accumulation of these nutrients in vegetation biomass. Although nutrient accumulation was greater in older stands, nutrient flow rates were not much different between stand ages. This indicates that the internal cycling of nutrients in young stands was as active as that in mature stands.

Denitrification activity was minimal in all aspen stands due to low soil C and soil moisture. Nitrogen loss by denitrification was limited in the study sites due to low carbon and moisture in the soil. Litter decomposition and nutrient release were faster in young stands. Likewise, nutrient availability was greater in young stands and became less as the stands grew older. Soil N mineralization was significantly greater in young stands. The N mineralization rates were affected by soil moisture conditions in the field. Sites with high water table retained more moisture in the topsoil and led to nitrogen mineralization rates 2-3 times greater than the rates on other sites. Study results indicate that nutrient cycling processes were accelerated in young aspen stands with an increased level of available nutrients in the soil.

Table 5. Estimated annual fluxes of nutrients (kg/ha/yr) in aspen stands at three different ages

Flux	Mature	Mid-age	Young	Flux	Mature	Mid-age	Young
		Nitrogen				*Calcium*	
Deposition	12.40	12.40	12.40	Deposition	24.50	24.50	24.50
Mineralization	26.63	32.69	77.51	Soil weathering*	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 sequestration	20.56	13.50	10.69	Plant sequestration	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
		Phosphorus				*Magnesium*	
Deposition	0.70	0.70	0.70	Deposition	3.40	3.40	3.40
Mineralization**	3.73	4.58	10.85	Soil weathering*	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 sequestration	11.36	6.91	4.03	Plant sequestration	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
		Potassium					
Deposition	12.90	12.90	12.90				
Soil weathering*	1.96	1.96	1.96				
Plant uptake	64.10	43.62	37.21				
Litterfall	16.70	14.26	17.39				
Plant sequestration	47.40	29.36	19.82				
Soil leaching	0.79	0.79	0.94				
Net soil budget	-33.33	-15.29	5.90				

* Soil weathering from Kolka and Grigal (in preparation)

** P mineralization was estimated from the ratio of N:P (1:0.14) in soil organic matter

Literature cited

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.

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.

Black, P. E. 1966. Thornthwaite's mean annual water balance. Silviculture General Utility Library Program GU-101. New York State University, College of Forestry. Technical Publication 92. 20 p.

Burton, D. L. and E. C. Beauchamp. 1984. Field techniques using the acetylene blockage of nitrous oxide reduction to measure denitrification. Can. J. Soil Sci. 64:555-562.

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

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.

Johnson, D. W. and S. E. Lindberg (eds.). 1991. Atmospheric deposition and forest nutrient cycling: a synthesis of the integrated forest study. Springer-Verlag, New York, N.Y. p. 707.

Keeney, D. R. 1982. Nitrogen - Availability indices. 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.

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.

Molchanov, A. A. 1963. The hydrologic role of forests. Israel Program for Scientific Translations, National Technical Information Service, Washington, D.C.

Myrold, D. D. 1988. Denitrification in ryegrass and winter wheat cropping systems of western Oregon. Soil Sci. Soc. Am. J. 53:412-416.

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.

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.

Perala, D. A. and D. H. Alban. 1982. Biomass, nutrient distribution and litterfall in *Populus*, *Pinus* and *Picea* stands on two different soils in Minnesota. Plant and soil 64:177-193.

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. NC-xxx (in press).

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.

Rapp, M., M. Cl. Leclerc and P. Lossaint. 1979. The nitrogen economy in a *Pinus pinea* L. stand. For. Ecol. Manag. 2:221-231.

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.

Robertson, G. P. and J. M. Tiedje. 1984. Denitrification and nitrous oxide production in successional and old-growth Michigan forests. Soil Sci. Soc. Am. J. 48:383-389.

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.

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.

Wagner, G. H. 1962. Use of porous ceramic cups to sample soil water within the profile. Soil Sci. 94:379-386.

4. Fertilizer study

The general objective of this study was to determine if Ca or N is limiting growth in field conditions, particularly on the sites used in the main nutrient cycling study and on some sites in the gradient study. The specific objectives were; (1) to determine if aspen growth responds to Ca or N fertilizer on sandy soils derived from non-calcareous till, (2) to determine the correlation between aspen growth and tissue concentrations of Ca or N, (3) to determine the correlation between Ca and N in aspen tissue and Ca and N in soil, and (4) to determine the correlation between aspen growth and soil N or Ca.

The study involved 9 aspen sites. Three sites were young stands on Omega soils including an Omega-like soil in Douglas County, Wisconsin. Three sites were mid-aged stands on these same soils, and three sites were young stands on Cloquet soils. Site and vegetation information are summarized in Table 6. Fertilizer treatments were control, Ca, N, and Ca + N. Nitrogen was applied as ammonium nitrate (NH_4NO_3) with a rate 90 kg N/ha/yr. Calcium was applied as calcium chloride ($CaCl_2$) with a rate 130 kg Ca/ha/yr. Half of the annual rate was applied in May and July of 1992; the full annual rate was again applied in April 1993.

Each fertilizer plot in the Omega soils was 20 x 20 m square and contained a growth subplot in its center. In mid-aged stands the growth plots were 10 x 10 m and were at least 20 m from other growth plots. In young stands the growth plots were 7 x 7 m and were at least 23 m from other growth plots. On the Cloquet soil, the treatment plots were 17 x 17 m, and the growth plots were as described above for young stands. Each treatment plot also contained two 4 m^2 circular shrub plots.

All trees in the growth plots were measured for dbh in November 1991 and November 1992 after leaf fall. Tree biomass growth was estimated using biomass equations developed by Perala and Alban (Allometric biomass estimators for aspen ecosystems in the upper Great Lakes, USDA For. Serv. Res. Pap. NC-xxx, in prep.):

$$\text{Biomass} = 0.12896 + \text{dbh}^{2.25154}\,(3.3146\ \text{dbh}^{0.54336})^{0.09401} \qquad (6)$$

Tree heights were measured in the growth plots in November 1991. In young aspen stands, only odd number trees were measured. The young stands were measured again for tree height in 1992.

Pre-treatment leaf samples were collected during August 26-29, 1991. For both mid-age and young stands, three codominant trees just outside the growth plot were selected and one branch fully exposed to the sun in upper two thirds of the crown was collected. Leaves were separated from the branch; two leaves each from the top and bottom of the branch were discarded and the remaining leaves were pooled and oven-dried. Leaf samples were again collected from young stands on the Omega soil during August 11-19, 1992. Two to four codominant trees just outside the growth plots provided the samples. The sample trees were cut at the base and tree height, crown length, dbh, and crown base diameter were

Table 6. Stand characteristics of the fertilizer study sites

Sites	Stand age	Tree no.	Basal area	Tree ht.	Site index	Location	Soil series
	yr.	#/ha	m^2/ha	m	m (50)		
FM1	33	1450	21.4	17.2	22	Cloquet, MN	Omega
FM2	27	2450	16.4	14.4	21	Cloquet, MN	Omega
FM3	28	2250	16.1	12.9	19	Douglas Co.	Omega/Vilas
FY1	10	9945	6.5	5.8	18	Cloquet, MN	Omega
FY2	10	9031	6.9	6.1	19	Cloquet, MN	Omega
FY3	13	11224	5.3	4.5	14	Douglas Co.	Omega/Vilas
FC1	13	7296	5.8	6.5	18	Cloquet, MN	Cloquet
FC2	13	8571	6.5	6.5	18	Cloquet, MN	Cloquet
FC3	13	9592	6.1	5.5	17	Cloquet, MN	Cloquet

measured. The shoots on the crown were then separated into four piles, upper or lower half of crown and long shoots or short shoots. Short shoots generally contained less than seven leaves. Leaves including petioles were then stripped from one-third of the shoots in each of these four piles was used to estimate total leaf biomass, nutrient concentration and nutrient content of the leaves. The samples were ground with a Wiley mill (20 mesh) for nutrient analysis. The leaves were oven-dried at 65°C for total N by Kjeldahl method and for P, K, Ca, and Mg by ICP spectrophotometry.

Soil samples were collected from the A and B horizons in November 1991 and analyzed for soil pH, CEC, organic matter, and nutrients. One soil profile description was made for each 4-treatment replicate. Soil samples for physical analysis were taken from each horizon in the soil pits.

Fertilizer treatment effects on stand growth, leaf weight, and leaf nutrients were tested by ANOVA with SYSTAT statistical software. Average leaf nutrient concentrations were obtained by dividing total leaf nutrient content by total leaf weight. Relationships between stand growth and plant nutrients were evaluated by linear and curvilinear regression with SYSTAT statistical software.

The fertilizer treatments had no significant effect on biomass growth (Fig. 1). However, when the data were analyzed separately for each soil and age class grouping, N fertilizer did produce a significant growth increase on the young stands in the Cloquet soils (Fig 2). Calcium treatment had no effect on biomass growth in similar types of analyses. The fertilizer effect on stand growth will be

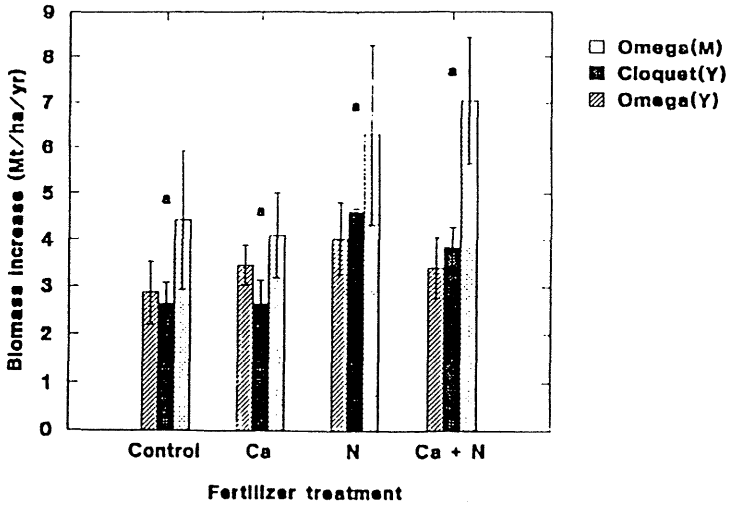


Figure 1. The 1992 biomass growth of aspen in response to fertilizer treatments. The same letter indicates that treatment effect on tree growth is not significantly different at alpha = 0.05. The standard error of each mean is also presented.

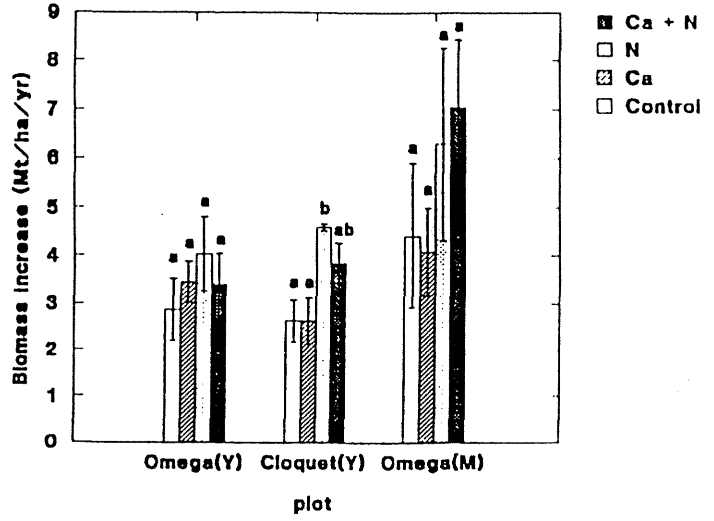


Figure 2. The 1992 biomass growth of aspen in response to fertilizer treatments. Fertilizer effects are compared within each group and soil type. The same letter indicates that treatment effect on tree growth in each age group and soil type is not significantly different at alpha = 0.05. The standard error of each mean is also presented.

better evaluated following more years of fertilization and stand growth.

Leaf Ca concentrations varied with leaf position, branch type, and site of collection. The concentration was highest in lower short shoots (LS) and lowest in upper long shoots (UL). Average leaf Ca concentration was highest in Ca + N plots and lowest in N plots, possibly as a result of growth dilution. Leaf Ca concentration was not affected by Ca-only fertilization. Among sites, treatments changed leaf Ca concentrations the most on the Wisconsin site (Table 7).

Leaf N concentrations did not vary significantly within the crown. Leaf N concentrations were significantly higher in N-fertilized plots than in the controls. When all sites were pooled, leaf N concentration increased with N and N+Ca treatments.

Tree biomass growth was positively related to leaf Ca and leaf N concentrations with relatively low correlation coefficients. The regression equations were:

$$\text{Biomass increase} = 0.679 + 3.983\ (\text{Leaf Ca}) \quad (R^2 = 0.192) \tag{7}$$

$$\text{Biomass increase} = -25.756 + 20.388\ (\text{Leaf N}) - 3.461\ (\text{Leaf N})^2 \quad (R^2 = 0.352) \tag{8}$$

Vector analysis of leaf concentrations, leaf nutrient content and biomass growth showed that neither Ca nor N was limiting aspen growth. First year results such as these indicate that the stands were not grossly deficient in either Ca or N but subsequent years of measurement are needed to determine if the stands are deficient at less than very severe levels.

This type of study requires at least 4 years of observation before any conclusions can be drawn. Therefore, these results are viewed as preliminary. Added calcium did not improve growth on any of the sites during the first year after fertilization. Added nitrogen may have improved growth on most sites, but the increase was only statistically different on young stands on one of the soils. A preliminary pot study indicated that most of the nutrients and the nutrient balance of the entire stand depends on the A horizon of the soil.

Table 7. Average leaf Ca and N concentrations in young aspen trees after first-year fertilizer treatments. The same letter indicates that treatment effect on leaf nutrients is not significantly different at each location at alpha = 0.05.

Leaf nutrient	Soil	Fertilizer treatment			
		Control	Ca	N	Ca + N
Ca	Omega	0.74a	0.70a	0.74a	0.76a
	Omega/Vilas	0.57b	0.68c	0.45a	0.78d
N	Omrga	2.37a	2.57ab	2.61b	2.72b
	Omega/Vilas	2.24a	2.25b	2.52c	2.38b

Future activities to complete this study are measurements in the 4th year (1995) of tree dbh, tree height, shrub base diameter at 15 cm aboveground, leaf nutrients (Ca and N), and tree mortality. If growth differences are found, a more detailed vector analysis will be made to determine which elements are limiting. Complete soil information will also be collected in the 4th year including soil pH, soil nutrients, soil N mineralization, and soil water at 50 cm depth. Timmer analysis will be done in the 4th year, and the relationship between leaf nutrients and soil nutrients and between aspen growth and soil nutrients will be evaluated.

A.6. Benefits: Knowledge gained would allow estimation of the process of nutrient cycling including inputs and outputs and outputs under different specie-site and management situations. The results would be inputs to the calibration and validation of the models in objective C.

B. ESTIMATING STATEWIDE IMPACTS (leaders: Burk, Cooper)

B.1. Narrative: Important to the analysis of harvesting impacts across the state is knowledge of what site specific study impacts imply for broad landform, soil and forest type combinations. For years one and two of the study the objective will be to validate the models developed in objective C by applying them to a limited number of sites. This work will provide the background for use of the models plus measurements on additional sites in years three and four of the study. The goal for model usage in these later years is extrapolation to a state-wide basis. Achieving this goal will involve use of geographic information systems (GIS) and synthesis of landform, soil type, forest cover type and harvesting patterns statewide. These same (objective B) sites would also be used as necessary to conduct the gradient study and possibly part of the fertilizer study described under objective A.

B.2. Procedures: In the first two years, existing reports and unpublished data from files would be acquired for model application. As part of that, the major geomorphic regions of the state and respective portions of commercial forest land would be identified. This would separate parent material and landform combinations and probably result in 15-20 regions. Subsequently information on vegetation and soil characteristics would be obtained for 2 to 5 sites chosen to represent some of these regions. These 2 to 5 sites will be measured to provide a basis for model parameterization and application for validation trials. Specifically, we would select stands of the major forest types on each soil type in a region to cover young, intermediate and mature age classes. This would provide data for an age based cross-section analysis to approximate how individual stands might develop over time. In years three through four this sample of sites would be expanded to approximately 20-30 to cover more of the parent material and landform combinations present.

Each site will be a minimum of two hectares in size. At each selected site the nutrient status of the vegetation (concentrating mainly on aspen) and soil will be assessed. This data collection will occur on two 0.05 hectare plots established at each site. Tree overstory information collected will include stem wood and bark samples (cores) and leaf tissue samples from six trees on each plot to be analyzed in the lab for nutrient content. Likewise, soil samples will be taken from each plot for nutrient analysis. Samples for a given site will be pooled for analysis. These and other observations would be similar to those collected under objective A, but with less frequent and/or less intense sampling. Again, sampling and existing data and relationships would be used judiciously to control costs. Specific measurement requirements could be refined as work on objective C progresses.

Observations made on these 20-30 sites will ultimately be used as inputs to the model of objective C to develop large area scenarios in the third and fourth years of the study. The GIS will be used to expand the study site results to larger areas. In effect the GIS will allow these data to be correlated with soil, vegetation, climatic, hydrologic and other layers in a statewide geographic information system (see following paragraph) and subsequent extrapolation of impacts of harvesting scenarios as described under objective C. The study areas under objective A would be a subset of these sites.

Reference data for geographic information system analysis will be assembled (or augmented as it may already exist) to include landform, soil type, and forest type data. Much of that is or will be available from other research or projects in the University (including LCMR projects), the Land Management Information Center (LMIC) and the Department of Natural Resources. The GIS will provide estimates of the areal extent of various landform combinations for aspen stocked areas. Based on preliminary results from objectives A and C, various landform and soil type strata thought to represent different potentials of nutrient deficiencies will be defined. To the extent the GIS (and associated data) are organized early, it will also be used to identify potential locations to sample according to the study design specifications.

References on motivation and procedure are:

Bates, P. C., C. R. Blinn and A. Alm. 1989. A survey of the histories of some poorly regenerated aspen stands in northern Minnesota. In: Proc. Aspen Symp. '89. USDA Forest Service Gen. Tech. Rep. NC-140.

Daddow, R. L. and G. E. Warrington. 1983. Growth-limiting soil bulk densities as influenced by soil texture. USDA Forest Service Watershed Systems Dev. Group, Fort Collins, CO. Report WSDG-TN-0005. 17 p.

Ruark, G. A., D. L. Mader and T. Q. Tatter. 1982. The influence of soil compaction and aeration on the root growth and vigor of trees - a literature review. Part 1. Arbor. J. 6: 251-265.

Shields, W. J.,Jr. and J. G. Bockheim. 1981. Deterioration of trembling aspen clones in the Great Lakes Region. Can. J. Forest Res. 11:530-537.

B.3. Budget:

	LCMR funds	Matching funds
Amount Budgeted:	$34,000	$0
Balance:	$0	$0

B.4. Timeline for Products/Tasks:

	Jan91	Jul91	Jan92	Jun92	Jan93	Jun93
Study site identification	--------	-------|				
Field observations		-------|		---------|		----|...
Laboratory analysis			----------	----------	----------	-|...
Synthesis				----------	----------	-|...

B.5. Status:

Final status report for July 1, 1993: A small scale (1:1,000,000) map (Cummins and Grigal, 1981) provided general information regarding parent material, landform, and soil great groups necessary for stratification of site locations. Sampling methodology helped overcome the spatial variability of the surface soil at the sites. Thirteen locations in the state concentrated on coarser parent materials and parent materials low in carbonates across the aspen growing region were selected. Site selection criteria were; public land, well-stocked stands of quaking aspen (>40 years old), soils similar to map units described in the map of Cummins and Grigal (1981), soils more likely to experience nutrient depletion due to shortened rotations (sandy and coarse-loamy soils and low carbonate parent material soils), and sites that can provide data for statewide validation and calibration of forest growth models based on a few intensively-studied sites.

Vegetation was sampled with synecological coordinates (syncords). Syncords represent a method of determining site quality as a function of existing vegetation. Syncords are values that mathematically represent the dominant moisture, nutrient, heat, and light requirements of a plant species. They are scaled on a 1 to 5 relative-intensity scale, and have been previously rated according to the methods of Bakuzis and Kurmis (1978) for plant species in Minnesota. Each species (canopy, shrub, and ground flora) observed at a site is recorded. Location values are averages of all species at the site. Syncords will be used as a weighing variable in an aspen growth model. Trees were measured in variable radius plots with a 10 BAF prism. Diameter at breast height (dbh) was measured on all "in" trees. Height and age were measured from one representative tree per plot.

Surface soil samples were collected and analyzed for total C, total N, soil pH, bases, and bulk density. Soils within a distance of one meter of the plot center were collected with an auger to a depth of one meter. Collected samples were bulked in 25-cm increments and analyzed for soil pH, exchangeable bases, particle size, available water capacity, and bulk density.

Of the thirteen locations, four locations had sandy parent materials, two locations had coarse-loamy parent materials, one had loamy parent materials, three had loamy or loamy skeletal materials over rock, two fine-loamy over dense till, and one clayey parent material. Four locations had less than 1 cm O horizon probably due to extensive earthworm activity at the site. Natural soil drainage differences occured between subplots in the same location occurred 4 times. Loamy substrata at 2 of the sandy locations likely reduced the effect of the sandy parent material on tree growth. Organic carbon ranged from 3.5 percent to 14.15 percent. Particle sizes ranged from: sand 4 to 94 percent; silt 3 to 77 percent; and clay 1 to 47 percent. Percent coarse fragments (>2mm) were less than 1 percent in the lacustrine sites to 42 percent at some Lithic subgroup sites. Soil chemical data for each layer sampled at the sites showed: cation exchange capacity 0.39 to 36.5 meq/100g; soil pH 4.9 to 8.0; Bray phosphorus 1 to 14.15 ppm; potassium 6 to 265 ppm; calcium 41 to 5734 ppm; magnesium 7 to 1029 ppm; and aluminum 1 to 604 ppm.

Most stands had significant components of other tree species. Sites in the western part of the state had higher nutrient syncord values than the eastern locations. Syncords for moisture ranged from 1.9 to 2.9 and nutrients ranged from 2.0 to 3.7. Site index ranged from 19.5 to 22.9 m (50 yr). Basal area ranged from 20.7 to 41.4 m^2/ha. Stand age for "mature" stands varied from 45 to 110 years.

The results show that the sites sampled represent many of the wide range of soils in the aspen growing region of Minnesota. Soil characteristics determined in the laboratory indicate that the sites provide for a wide range of soil physical, chemical, and morphologic parameters. Soils and aspen stands sampled will provide data necessary for both nutrient cycling and atmospheric change analyses.

Literature cited

Bakuzis, E. V. and V. Kurmis. 1978. Provisional list of synecological coordinates and selected ecographs of forest and other plant species in Minnesota. Staff Series Paper Number 5, Dept. of Forest Resources, University of Minnesota, St. Paul. P. 30.

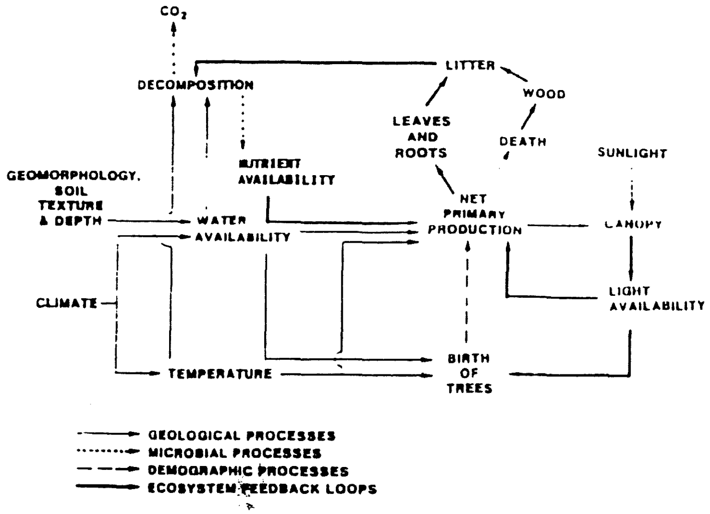
Cummins, J. C. and D. F. Grigal. 1981. Legend to map: soils and land surfaces of Minnesota, 1980. MN Agri. Exp. Sta. Miscellaneous Publ. 11. p. 59.

B.6. Benefits: Provide a basis for extrapolation from the intensive studies in objective A to region and statewide conditions and to provide inputs to the model in objective C for scenario development over the next several decades given anticipated forest management intensification and atmospheric change scenarios.

C. MODELLING ALTERNATIVE MANAGEMENT SCENARIOS (leaders: Burk, Ek, Pastor, Phillips)

C.1. Narrative: This objective would incorporate study results as refinements of a model of forest growth and nutrient cycling dynamics. That modelling capability would be essential to long term (2-10 decade) simulation and study of the implication of rotation length choice together with potential atmospheric changes. It should also assist in shorter term projections. The model must also help translate research results to resource managers in a manner that facilitates informed applications in management.

C.2. Procedures: Many models have been developed for the purpose of quantifying growth and yield for timber management. Many others have been developed to describe forest succession of long time periods. We propose to utilize portions of the recent LINKAGES succession or gap model and portions of the STEMS regional forest growth model. A schematic of the hypothesized feedbacks and linkages in the resulting model is shown below:



The LINKAGES model also incorporates rudiments of soil processes including soil moisture, carbon and nutrient cycling. We would add components of other models, such as those being developed for nutrient flux and those with physiologically based characterizations of growth. A major refinement of LINKAGES will be the addition of two modules, one dealing with the availability of calcium to trees and the other with the response of trees to calcium. The corresponding modules or models to be integrated with LINKAGES include a new model of mineral weathering, and NucM, a model of cation cycling in forests. In addition we will use the data collected and analyzed under objective A on the growth response of aspen to calcium and nitrogen to refine the growth response component of the model. The intent is also to facilitate use of radiation, temperature, and moisture (including transpiration) in the model. However, incorporating that detail will also require significant scale up procedures to be practical. The aim is a composite model useful to forestry practice with biological and ecological realism and statistical precision.

Summers, K., S. Gherini, R. Munson, R. Hudson, D. Johnson, and L. Pitelka. 1990. The IFS nutrient cycling model: overview and application. TetraTech, Lafayette, CA. Unpublished mimeo.

Sverdrup, H. and P. Warfvinge. 1990. Modelling chemical weathering rates of primary silicate minerals: Consistency between observed field rates and model predictions. Unpublished mimeo.

C.3. Budget:

	LCMR funds	Matching funds
Amount Budgeted:	$26,000	$3,000
Balance:	$0	$0

C.4. Timeline for Products/Tasks:

	Jan91	Jul91	Jan92	Jun92	Jan93	Jun93
Literature review	--------|					
Model refinement		----------------|				
Calibration			----------|			
Validation			-------------------|			
Scenario development					----------------|	
Synthesis					-------------|	

C.5. Status:

Final status report for July 1, 1993: The ecosystem model LINKAGES was refined to allow for input of typical field plot data. Field data were compiled from FIA data. Specifically, average stands were generated using FIA stands of medium density, relatively young age, and medium to high aspen content for the NE, Central, and SE regions of Minnesota. These average stands contained information on species, dbh, and trees per acre. Individual tree information from 1/12th hectare plots is required to run LINKAGES. Average trees per acre were converted to trees per hectare and expanded into tree lists. A 1/12th hectare plot was generated by first sorting the average tree list by species and dbh, then randomly choosing the first tree of the plot from the first twelve trees of the sorted tree list, and systematically choosing every twelfth tree thereafter.

Several other site-specific variables were obtained to allow for relative comparisons on the basis of soil and climate variations. In each region studied, three well-drained soil series common to aspen were selected, one each of course, medium, and fine texture. Field moisture capacity, wilting point, humus weight, and nitrogen content in the humus were calculated from the soil series information. A representative city in the region was used to draw latitude and longitude, growing season, annual precipitation, and temperature from weather records.

Simulating stand development with LINKAGES allowed for study of long term effects of initial conditions. Interestingly, in all the cases studied, simulated mortality of aspen was extreme with little or no ingrowth. Even in circumstances when aspen represented a substantial portion of the overall stand basal area and biomass (20-100%), the percent of trees representing aspen was less than 10%. at the end of 100 years of simulation. Initially high composition aspen stands were still generally higher in terms of percent biomass and basal area than low composition aspen stands in the same region with similar soils. Additionally, as soil texture became finer, aspen occupied a greater percentage of the basal area and represented a greater portion of the biomass. Regional differences were also observed. Region four showed the greatest percentage of aspen at the end of 100 years simulation. These relative results are informative. However, they also suggest the model needs further testing and possible refinement with respect to mortality. That refinement is feasible and will continue.

C.6. Benefits: This modelling capability would serve as a basic tool for a wide range of ecological and silvicultural analyses important to environmental impact assessment and forest management planning. These capabilities are essential to approach possible environmental changes in the next several decades whether they be of natural or anthropogenic origin.

IV. EVALUATION

A number of nutrient cycling studies have been conducted, but questions remain for certain soil and species combinations. For the 91-93 biennium this project can be evaluated by its success in:

- assembling a quality data set for understanding nutrient cycling on the study sites
- synthesizing existing data, new data and published results into a clear picture of the soils/nutrient/atmospheric change/forest management situation for the study sites.
- developing relationships for extrapolating results to other parts of the state
- incorporating the results into a computer simulation model useful to forest managers, ecologists and other interested parties for studies of the implications of harvesting, management and climate change.

This evaluation can also be developed by comparison to similar studies being conducted in other regions for different species-site combinations. Additionally, the study should highlight Minnesota and its institutional capability and study sites as valuable scientific assets.

On a longer time scale, the project will establish the basis for an understanding of the relationships between forest ecosystem processes, forest management and atmospheric change. The extrapolative utility of the study result will be a key criteria for evaluation.

V. CONTEXT

A. This is a new project intended to assist forest management decisions. However, it will be able to draw on previous research and study sites in the state. The project would provide important information on the implications of management choices of species, regeneration technique, rotation length and utilization level. This information will provide much greater definition than what we know today. It is crucial to management for sustained long term productivity. Results would also be central to the planned generic environmental impact statement on timber harvesting. The project is assisted by several previously funded LCMR projects. This is planned as a four to eight year study, with a variety of intermediate results. If funded for the first two years we would ask for

The resulting model will be an individual tree based simulator with some capability for treating vegetation, soil and climate interactions. Tree growth will be affected by nutrient availability, light, soil moisture, or degree days, whichever is most restrictive for each tree. Decomposition of litter in the model will be influenced by species and climate and help determine nutrient availability. The model will go beyond existing ones in incorporating the following specific aspects:

- -Concise and accurate description of the known biology of the system
- -Improved characterization of soil, and weather impacts on growth and succession including
    - -Mineral weathering including calcium
    - -Multinutient tree response model including calcium
- -Biometrical precision
- -Output which promotes wide usage and understanding of succession and growth and acid deposition and climate change implications
- -Rapid execution to facilitate use with large data sets corresponding to initial conditions
- -A framework which facilitates incorporation of growth/CO_2 functions

In developing the model, communication with the co-investigators working on objectives A and B is essential to ensure that needed model inputs are developed by the field studies. Starting with existing equation forms, models will be developed with appropriate statistical techniques which show the relationship between growth, stand and tree level variables, soil and weather variables. These techniques will involve linear, nonlinear, and time-series analyses. As the model is refined from study site data, statistical resampling procedures will be used as a means of prediction evaluation.

Given recent measurements of the USDA Forest Service Forest Inventory and Analysis (FIA) plots statewide and several forest management and climate change scenarios, forest impact predictions will be generated for the state using the new composite model. This involves applying the model to FIA data initial conditions and using the most accepted climate scenarios and associated atmospheric conditions. The scenarios will also be displayed and studied using the geographic information system layers described under objective B.
In developing those scenarios, we would attempt to develop a matrix of responses based on combinations of temperature, precipitation and CO_2. We would also develop such scenarios for alternative harvest utilization practices and various species site matching. Results would also be assembled in standard FIA tables describing future forests in terms of variables of commercial and ecological interest. Additionally, results would be illustrated by maps via the geographic information system in the University's Remote Sensing Laboratory.

References on these models and procedures are:

Burk, T. E., R. Sievanen, and A. R. Ek. 1990. Construction of forest growth models based on physiological principles. In: Aspen Symposium Proc. '89. USDA Forest Service Gen. Tech. Rept. NC-140. pp: 103-111.

Belcher, D. M. 1981. User's guide to STEMS (Stand and Tree Evaluation and Modeling System). USDA Forest Serv. Gen. Tech. Rep. NC-70, 49p.

Botkin, D. B., J. F. Janak, and J. R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. J. Ecology 60(3):849-872.

Burk, T. E. 1988. Prediction error evaluation. In: Forest simulation systems. Proceedings of IUFRO Conference. L. C. Wensel and G. S. Biging, Eds. Univ. CA, Div. Agric. and Natural Resources, Bull. 1927. pp. 81-88.

Cleary, B. D. and R. H. Waring. 1969. Temperature: collection of data and its analysis for the interpretation of plant growth and distribution. Can. J. Botany 47:167-173.

Cook, E. R. 1987. The use and limitations of dendrochronology in studying effects of air pollution on forests. In: Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems. T.C. Hutchinson and K.M. Meema (eds.) NATA ASI Series, Vol. G16, pp. 277-290.

Davis, M. B. and D. B. Botkin. 1985. Sensitivity of cool temperate forests and their fossil pollen record to rapid temperature change. Quaternary Res. 23: 327-340.

Eriksson, M. E. 1989. Integrating forest growth and dendrochronological methodologies. Ph.D. Thesis, Univ. Minn., St. Paul, MN. 303p.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecological Monographs 53.

Olson, J. S., J. A. Watts, and L. J. Allison. 1983. Carbon in live vegetation of major world ecosystems. ORNL-5862. Oak Ridge National Lab., Oak Ridge, TN.

Pastor, J. and W. M. Post. 1985. Development of a linked forest productivity-soil process model. Oak Ridge National Lab., Envir. Sciences Div. Pub. No. 2455. 162p.

Pastor, J. and W. M. Post. 1986. Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. Biogeochemistry 2:3-27.

Pastor, J. and W. M. Post. 1988. Response of northern forests to CO_2-induced climate change. Nature 334:55-58.

Post, W. M. and J. Pastor. 1989. An individual-based forest ecosystem model for projecting forest response to nutrient cycling and climate changes. In: Forest simulation systems. Proc. IUFRO Conf. L. C. Wensel and G. S. Biging, Eds. Univ. CA, Div. Agric. and Nat. Res. Bull. 1927. pp. 61-74.

Reed, K. L. and R. H. Waring. 1974. Coupling of environment to plant response: a simulation model of transpiration. Ecology 55:62-72.

Shugart, H. H., S. B. McLaughlin, and D. C. West. 1980. Forest models: their development and potential applications for air pollution effects research. IN: Presented at Symp. on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems, June 22-27, 1980, Riverside, CA.

Smith, W. H. 1985. Forest Quality and Air Quality. J. Forestry 83(2):82-92.

Solomon, A. M. and H. H. Shugart. 1984. Integrating forest-stand simulations with paleoecological records to examine long-term forest dynamics. Pp. 333-356 in Agren, G.I. (ed.). State and Change of forest Ecosystems. Swedish Univ. Agric. Sciences Rep. Nr. 13. Uppsala, Sweden.

Solomon, A. M. 1986. Transient response modelling of forests to CO_2-induced climate change:simulation modelling experiments in eastern North America. Oecologia 68:557-569.

approximately similar funding for the next biennium. The investigators are confident that they can develop support beyond the fourth year. In fact, the proposed initial funding for four years could lead to Minnesota being a lead national site for such research.

B. This work will supplement previous by adding species and site quality specifics pertinent to forests and their management in Minnesota.

C. There have been no past LCMR funds used in this area.

D. Not applicable

E. Biennial budget system program title and budget: Not available at this time.

VI. QUALIFICATIONS

A. Program manager

Dr. Alan R. Ek, Professor and Head
Department of Forest Resources
University of Minnesota, St. Paul, Minnesota

Ph.D. Forest measurements, Oregon State University, 1969.
M.S. Forestry, University of Minnesota, 1965.

Dr. Ek has experience in project management and the modelling of forest stand growth. His primary role will be as program coordinator to ensure that project components considered by co-investigators come together well and as a co-investigator under objective C in adapting the existing LINKAGES model of forest growth and nutrient cycling to meet study objectives.

B. Major cooperators/co-investigators

1. Dr. David H. Alban, Research Soil Scientist
Forestry Sciences Laboratory
USDA Forest Service, North Central Forest Experiment Station
Grand Rapids, MN

Ph.D. Forest Soils and Ecology, Washington State University, 1967.
B.S. Forest Management, University of Washington, 1964.

Dr. Alban specializes in forest soils research. His role will be liaison with the USDA Forest Service North Central Forest Experiment Station and advising on study design, notably for objective A.

2. Dr. Thomas E. Burk, Associate Professor
Department of Forest Resources
University of Minnesota, St. Paul, MN

Ph.D. Forest Biometrics, University of Minnesota, 1981.
M.S. Statistics, University of Minnesota, 1980.
M.S. Forestry, University of Minnesota, 1978.

Dr. Burk's specializes in experimental design and the modelling of tree growth. His primary roles will be in analysis and validation of model components, design of the sampling scheme for objective B and integration of existing models in objective C.

3. Dr. Terence H. Cooper, Associate Professor
Department of Soil Science
University of Minnesota, St. Paul, MN

Ph.D. Soil Science, Michigan State University, 1975.
M.S. Soil Science, Michigan State University, 1969.

Dr. Cooper's specialization is in soil morphology and classification. His primary roles will be under objective A concerning mineral weathering and under objective B in developing forest soil interpretations for study sites and a broader range of common forest soils.

4. Dr. David F. Grigal, Professor
Department of Soil Science
University of Minnesota, St. Paul, MN

Ph.D. Soil Science and Forestry, University of Minnesota, 1968.
M.S. Forestry-biostatistics, University of Minnesota, 1965.

Dr. Grigal specializes in forest ecology and soils. His primary role will be under objective A in the collection of nutrient cycling data, including weathering information and in assessing growth responses. He will also assist in study design including that for objective B.

5. Dr. John Pastor, Research Associate
Natural Resources Research Institute
University of Minnesota, Duluth, MN

Ph.D. Forestry and Soil Science, University of Wisconsin, Madison, 1980.
M.S. Soil Science, University of Wisconsin, Madison, 1977.

Dr. Pastor's specializes in forest ecology with particularly emphasis on modelling soil processes. His primary role will be under objective C in modelling nutrient and carbon cycling with the LINKAGES model and scenario development and in study design to ensure the collection of critical modelling inputs. However, he will also advise on design for objective A.

6. Dr. Donald A. Perala, Principal Silviculturist
Forestry Sciences Laboratory
USDA Forest Service, North Central Forest Experiment Station
Grand Rapids, MN

Ph.D. Forestry, University of Minnesota, 1987.
M.S. Forestry, University of Minnesota, 1963.

Dr. Perala's specializes in silvicultural research. His role will be liaison with the USDA Forest Service North Central Forest Experiment Station and advising on study design, notably for objective A.

7. Dr. Michael J. Phillips, Forest Soils Program Supervisor
Division of Forestry
Minnesota Department of Natural Resources
St. Paul, MN

Ph.D. Forest Soils, University of Canterbury, New Zealand, 1981.
M.S. Forest Soils, Oregon State University, 1976.

Dr. Phillip's is a specialist in the area of forest soils. His role will be liaison with the Department of Natural Resources in the selection of study sites, advising on management data needs, and assisting in study design and interpretation of study results to the forestry community and the public. He will have a primary role in integrating study results and recommendations into ongoing and future forest management programs.

8. Dr. Edward I. Sucoff, Professor
Department of Forest Resources
University of Minnesota
St. Paul, MN

Ph.D. Plant Physiology, University of Maryland, 1960.
M.S. Forestry, University of Michigan, 1956.

Dr. Sucoff specializes in tree physiology and plant water relations. His primary role will be under objective A to help incorporate plant water relations and CO_2 and carbon dynamics into data collection, analysis and modelling. He will also lead the gradient analysis component of this objective.

9. A postdoctoral research associate and several graduate research assistants will also be hired to assist the project manager and co-investigators in project execution.

VII. REPORTING REQUIREMENTS

Semiannual status reports will be submitted not later than January 1, 1992, July 1, 1992, January 1, 1993 and a final status report by June 30, 1993.

A. Significant Problems

No significant problems have arisen to date except that we are slightly overbudget with respect to field travel expenses and sample analysis cost. This may force a reduction in the field effort or postponing lab analyses. The problem has been alleviated in part by support from related projects.

Disapproval of two more years of additional funding for this project may cause discontinuation or postponement in some long-term studies involved. The established research plots and records will be maintained as far as possible for future continuation of the studies when more funding becomes available. However, lack of funding for specific study site protection from hare and beaver damage may lead to the loss of some study plots.