Regional Copper-Nickel Study

Phytotoxicology Monitoring Proposal

Authors: Barbara Coffin
William A. Patterson

Contributing Editor: Gerald A. Lieberman

Table of Contents

PHYTOTOXICOLOGY MONITORING PROPOSAL

INTRODUCTION TO THE REGIONAL COPPER-NICKEL STUDY

ABSTRACT

INTRODUCTION TO THE REGIONAL COPPER-NICKEL STUDY

The Regional Copper-Nickel Environmental Impact Study is a comprehensive examination of the potential cumulative environmental, social, and economic impacts of copper-nickel mineral development in northeastern Minnesota. This study is being conducted for the Minnesota Legislature and state Executive Branch agencies, under the direction of the Minnesota Environmental Quality Board (MEQB) and with the funding, review, and concurrence of the Legislative Commission on Minnesota Resources.

A region along the surface contact of the Duluth Complex in St. Louis and Lake counties in northeastern Minnesota contains a major domestic resource of copper-nickel sulfide mineralization. This region has been explored by several mineral resource development companies for more than twenty years, and recently two firms, AMAX and International Nickel Company, have considered commercial operations. These exploration and mine planning activities indicate the potential establishment of a new mining and processing industry in Minnesota. In addition, these activities indicate the need for a comprehensive environmental, social, and economic analysis by the state in order to consider the cumulative regional implications of this new industry and to provide adequate information for future state policy review and development. In January, 1976, the MEQB organized and initiated the Regional Copper-Nickel Study.

The major objectives of the Regional Copper-Nickel Study are: 1) to characterize the region in its pre-copper-nickel development state; 2) to identify and describe the probable technologies which may be used to exploit the mineral resource and to convert it into salable commodities; 3) to identify and assess the impacts of primary copper-nickel development and secondary regional growth; 4) to conceptualize alternative degrees of regional copper-nickel development; and 5) to assess the cumulative environmental, social, and economic impacts of such hypothetical developments. The Regional Study is a scientific information gathering and analysis effort and will not present subjective social judgements on whether, where, when, or how copper-nickel development should or should not proceed. In addition, the Study will not make or propose state policy pertaining to copper-nickel development.

The Minnesota Environmental Quality Board is a state agency responsible for the implementation of the Minnesota Environmental Policy Act and promotes cooperation between state agencies on environmental matters. The Regional Copper-Nickel Study is an ad hoc effort of the MEQB and future regulatory and site specific environmental impact studies will most likely be the responsibility of the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency.

Abstract

A proposal for a long-term phytotoxicology monitoring program to be instituted in northeastern Minnesota with the initiation of the development of copper-nickel resources is discussed. The development of an environmental monitoring program is essential if both the natural functioning of the ecosystems of northeastern Minnesota is to be understood and the early detection of destructive alteration predicted. Vegetation is an important component of environmental monitoring. There is a need to relate air and water measurements to biological organisms in order to define actual levels of toxicity and to establish effective air and water quality standards. Plants are natural indicators of toxicity levels, low-level contamination, and ecosystem alterations caused by industrial pollutants.

The organization and methods of the few established phytotoxicology monitoring programs are reviewed. Two alternative designs for phytotoxicology monitoring programs in Minnesota are proposed: a permanent phytotoxicalogy laboratory and independent-contract monitoring. Monitoring techniques were selected and discussed that could be utilized in either design. Comprehensive monitoring should include methods which sample the area on a regional scale (e.g. aerial photography, lichen mapping), on permanent plots (e.g. quantitative measurements, plant pathology studies) and by use of experimental research (e.g. bioassay studies). Data gathered from these studies should be integrated with physical, chemical, and other biological measurements so that a holistic approach is possible in the analysis and impact assessment phase of monitoring.

Minnesota has the rare opportunity to establish a pre-operational, operational, and post-operational monitoring program. The study of symptomatic expression of plants to a contaminated environment is essential if we are to understand the immediate and long-range impact of copper-nickel mining in Minnesota.

1.0. INTRODUCTION

This report presents a proposal for a long-term phytotoxicology (the study of the response of plants to a toxic environment) monitoring program to be instituted in northeastern Minnesota with the initiation of the development of copper-nickel resources. This paper discusses the justification, organization, and methods that might be used to design such a monitoring program.

In April, 1975, the Copper-Nickel Task Force (CNTF) submitted a work plan for a study of the impacts of copper-nickel development. This work plan suggested that in addition to the data collected during the initial study, "data from the regional monitoring and inventory systems should continue to be collected until an undefined future date" (CNTF, 1975). With the completion of the Regional Copper-Nickel Study the data collected during 1976-1977 have been compiled and analyzed. The analysis provides an ecological characterization and baseline for the Regional Copper-Nickel Study Area. It also attempts to develop predictive measures of the potential impacts on various ecological parameters based on a set of possible perturbations which might be caused by mining activities. However, if long-term effects are to be detected and predicted there must be an on-going study continuing after the completion of the Regional Copper-Nickel Study which monitors these potential impacts.

This proposal in combination with long-term monitoring of physical, chemical, and other biological parameters would provide the people of Minnesota with a comprehensive understanding of patterns and changes in northeastern Minnesota on an ecosystem level. Alterations due to mining activity could be discovered before the effects were irreversible.

2.0. JUSTIFICATION

2.1. Ecosystem Monitoring

The development of an environmental monitoring program will be essential if both the natural functioning of the ecosystems of northeastern Minnesota is to be understood and the early detection of alteration predicted. Odum (1976) feels strongly that ecological studies must evolve "rapidly from component analysis (wherein factors and organisms are scaled and weighted as if they were independent entities with no interaction function) to more holistic approaches (wherein interactive and integrative properties are also included)." He reminds us of the familiar adage that the forest is indeed more than a collection of trees. According to Hays (1974), "Environmental monitoring should include the physical and biological environment related to the complex of climatic, edaphic (soils), and/or biotic (living things) factors which may be modified or devastated by copper-nickel extraction." There have been few opportunities nationwide to establish an ecosystem monitoring program that could be initiated prior to the operation of the potentially polluting industry. Minnesota has this opportunity Preoperational, operational, and postoperational monitoring must be a part of the proposed monitoring program.

One important component of the biotic aspect of an ecosystem study is the analysis of vegetation. Understanding the toxic response of plants if is necessary if we are to comprehend functional and structural changes at an ecosystem level. This paper explains the importance of phytotoxicology monitoring and describes possible methods by which these responses could be measured.

2.2. Vegetation—An Important Components of Ecosystem Monitoring

Air and water pollution is a fact in today's world of technology. The aesthetic degradation caused by a cloud of smog or a film of oil on a water's surface is obvious, but the toxic subtleties of sulfur dioxide, heavy metals, and other pollutants are not as easy to recognize and evaluate. The far-reaching implications of these contaminants become more obvious as we gain insight into the response of biological organisms.

The value of monitoring phytotoxic responses is questioned by some individuals. They feel that the monitoring of air and water quality is adequate for detecting the occurrence of damaging pollutants. Air and water quality are monitored on a long-term basis across the nation in both cities and in areas surrounding industrial complexes. These measurements do provide valuable information on the concentration level, distance from source, and speed of dispersal of a given pollutant; but, this information alone does not provide a complete understanding of the extent of influence of a polluting agent. There is a need to relate air and water quality measurements to biological organisms in order to better establish actual levels of toxicity.

Plants are a major component of the biota. That they are susceptible to injury by air and water pollutants is well established (Naegele, 1973; Dugger, 1974; Mudd and Kozlowski, 1975; Guderian, 1977). However, most studies are either laboratory experiments or post-morten examinations. There is a need for long-term studies where both individuals and plant populations are monitored in areas adjacent to the source of pollution.

Plant toxicology has not yet reached the level of sophistication of human and animal toxicology (Naegele, 1973). Most investigators have studied the visible and gross phytotoxic responses. These symptoms are usually the result of an acute response (exposure to a relatively high concentration of toxicant for a short period of time). More recently, plant pathologists have developed an increased awareness of the symptomatic expression of plants to chronic toxicant conditions (low level toxic exposure over longer periods of time). Research on acute and chronic responses of plants has been basically restricted to studies on individual species. Naegele (1973) feels that not only must there be more research on individual species but also that ~~emphasizes~~ the i~~mportance~~ of studying~~ing~~ plant population toxicology must be emphasized.

A review of pertinent literature demonstrates the need for further research in phytotoxicology. Plants are indicators of toxicity levels, low-level contamination, and ecosystem alterations. Monitoring vegetation not only adds a necessary dimension to a comprehensive ecosystem monitoring program, but also implements the use of pollutant indicators with unique capabilities.

2.2.1. Plants as Indicators of Toxicity Levels

Toxicity levels need to be determined for dominant plant species in northeastern Minnesota. Research has been conducted to assess the sensitivity of some species (Linzon 1966; Van Raay 1969; Lihnell 1968; Dreisinger and McGovern 1970; Environmental Protection Agency 1973; Davis and Wilhour 1976). However, definitive literature is lacking in most cases and generalizing results from one study to a different geographical area is often invalid.

The response of plants to both acute and chronic exposures should be measured and related to prevailing environmental conditions. Results from these studies would be important for understanding the implications of varying levels of pollutants emitted or discharged from an industry. The accumulation of air, water, and climatic monitoring data in association with records of plant injury response would provide the needed criteria for establishing air and water quality standards. Standards determined with this knowledge allow for the institution of emission controls that minimize injurious pollution episodes.

this has already been said, (P. 3)

Linzon (1966) found eastern white pine in the Sudbury, Ontario area to be susceptible to SO_2 pollution. Concentrations of atmospheric SO_2 over 655 mg/m^3 that persist for several hours have the potential to cause needle injury. Visible foliar injuries are further reflected in radial and volume growth decrement and tree mortality. Dreisinger and McGovern (1970) recorded the sensitivities of plants growing adjacent to air quality recording stations between 1954 and 1963 in Sudbury, Ontario. They found trembling aspen to be the most sensitive forest species and buckwheat the most sensitive agricultural species. Lihnell (1968) measured the sulphate content in leaf samples in order to map SO_2 pollution around SO_2-emitting industries in Sweden. His results support the assumption that high sulphate content of tree leaves correlates with SO_2 pollution.

μg?

logical progression?

The U. S. Forest Service is an example of an institution that could utilize the information gained from toxicity studies. Land managers could begin to understand the economic implications of pollutants and incorporate knowledge of species sensitivities into the selection of management alternatives and the distribution of funds for timber stand improvement.

Long-term studies of chronic pollutant contamination, conducted in the field, are essential before an accurate assessment of the impact of air and water pollutants on agriculture, forestry, and natural plant community productivity can be ascertained.

2.2.2. Plants as Indicators of Low-Level Contamination

Plants can provide information about low-level contamination that no other pollution indicator is able to ~~measure~~ provide. It is possible to use plants as natural integrators of heavy metal deposition and gaseous pollutant contamination.

Hawksworth and Rose (1970) feel that estimates based on lichens are probably more significant indicators of air pollution than quantitative chemical measurements made at a particular time. Lichens, because of their slow growth and long-live~~d habit~~s, provide an excellent bioassay system for monitoring, on a regional scale, the influence of industrial pollutants on plant growth (see section 4.3.2.2.)

Goodman et al. (1975) showed that moss suspended in mesh bags gives a more realistic understanding of airborne metal contamination than recording gages because of the natural response of moss to environmental variables. Rühling and Tyler (1970) found a terrestrial moss to be a good indicator of sorption and retention of heavy metals. Nash et al. (1975) has developed a technique for examining nonclimatic variation in widths of annual tree rings with special reference to air pollution. A study in Sweden by Westman (1974) used the pH of pine bark and two common tree lichens as indicators of air pollution. In addition, he used multiple regression analysis to determine the effect of air pollution on annual growth increments.

2.3.3. Plants as Indicators of Ecosystem Alterations

Complex changes are occurring in the structure and function of natural ecosystems due to contamination by accumulating toxic substances (Woodwell 1970). Many of the changes are subtle and as yet go largely undetected. At present the deficiencies that exist in our understanding of the interaction between pollutants and ecosystem stability make the quantification or modeling of impacts difficult at best. "Research to determine the relationships between air pollution and forest ecosystems must be given high priority because of the size and significance of these ecosystems in temperate regions and the numerous potentially-damaging interactions that have been identified" (Smith 1974).

The effects of air pollution on the structure, function, and economics of forest ecosystems have been discussed by several authors (Woodwell 1970; Linzon 1971; and Smith 1974). Woodwell (1970) examined the effects of chronic irradiation on a late successional oak-pine forest at Brookhaven National Laboratory in New York. Using this example as a prototype, he relates it to other disturbed ecosystems. He believes that there is a predictable pattern of change, "first a reduction of diversity of the forest by elimination of sensitive species; then elimination of the tree canopy and survival of resistant shrubs and herbs widely recognized as 'seral' or successional species or 'generalists'" (Woodwell 1970).

Smith (1974) divides the relationship between air pollution and forest ecosystems into three classes according to the level of pollutant present (Table 1). Class III relationships (acute damage, mortality) are the most visible effects of pollution and thus have been the most studied. Predictive modeling and abatement of potentially dangerous developments can be ~~averted~~ accomplished only when we understand Class I and II relationships. Research to define the extent of Class I (sink function) and Class II (subtle, deleterious effects) relationships must encompass the careful integration of field and experimental studies.

Linzon (1971) studied the long-term chronic effects of sulfur dioxide on yield, growth, and survival of eastern white pine in the Sudbury, Ontario area. Sulfur dioxide caused perennial foliage injuries resulting in smaller leaf growth, reduced annual radial increment growth, and increased tree mortality. Based on direct volume loss and mortality of white pine trees over a ten-year period an estimate of income loss was calculated. For white pine alone (which composed only 7.6 percent of the total productive forest area) a loss of $117,000 annually was estimated to occur in the Inner Fume Zone (approximately 720 square miles).

Plants are valuable indicators of ecosystem alterations. Woodwell (1970) demonstrates their importance in understanding the implications of change in the structure of ecosystems. Smith (1974) outlines the response and potential impact to an ecosystem when the function of plants is altered. Linzon (1971) demonstrates the economic impact of a pollutant on forest productivity.

3.0. ESTABLISHED PHYTOTOXICOLOGY MONITORING PROGRAMS

There is little precedent in this country or elsewhere for the establishment of a phytotoxicology monitoring program. Plant pathologists and ecologists have conducted studies on specific problems in isolated laboratories but funding for long-term, integrated studies has not been a priority. The flowchart (Figure 1) is intended to create a conceptual format organizing the tasks to be completed by a phytotoxicology monitoring program. Within this format there are many ways in which a monitoring program could be organized. The few phytotoxicology programs that do exist are examples of some of the options to consider (Linzon 1970; Taylor 1973a, 1973b; Willard 1977).

A phytotoxicology section of the Air Management Branch of the Ontario Ministry of the Environment was established in 1968. The objectives of this program "are to determine the degree and extent of air pollution injury on all types of vegetation throughout Ontario" (Linzon 1970). A staff of plant pathologists, agronomists, plant ecologists, and greenhouse and laboratory technicians attempts to attain the following objectives as outlined by Linzon (1970):

1) By investigating complaints concerning suspected air pollution injury to all types of vegetation, which includes forests, orchards, farm crops, and ornamental plantings, in both rural and urban areas. In doing this it is necessary to differentiate pollution injury from similar injuries caused by insects, disease, adverse weather, poor nutrition, and mismanagement.

2) By conducting surveillance studies in areas of concern where adverse effects on vegetation may occur as a result of emissions from existing or future sources of air pollution.

3) By carrying out practical research studies in controlled environment chambers on the effects of air pollutants on vegetation, in order to complement field investigations, to screen resistant plant species, and to determine air quality criteria which may be applicable for the protection of agriculture and forestry.

Examples of studies conducted by the phytotoxicology section have been published by McGovern and Balsillie (1975), McGovern (1975), and Balsillie, McGovern, and McIlveen (1975).

The San Bernardino National Forest is being monitored in an on-going study to assess the impact of oxidant air pollutants on a western coniferous forest ecosystem. This area was selected because of its proximity to the heavily populated coast of southern California and the evidence of encroachment of pollutants into the area (Taylor 1973). Researchers from the University of California and the U.S. Forest Service are cooperating in an effort to determine the impact of pollutants on the total ecosystem. Initially, a historical study was conducted to ~~characterize~~ determine the biological and physical characteristics of the area and to identify factors other than air pollutants which have affected the species distribution, health of organisms, and successional development of the forest ecosystems. The following monitoring techniques are some of the methods suggested for the on-going study:

1) The implementation of dendrochronology and X-ray techniques for measuring wood density to understand history of oxidant air pollution impact and predict future trends. This would be conducted in both contaminated and control areas.

2) Define successional trends by establishing permanent observation plots and determine ecological potential of major species through controlled environmental studies and ordination along gradients of important environmental variables.

3) Utilize aerial photography to define boundaries of contaminated area.

4) Investigate effects of oxidant air pollution on reproductive physiology of plants (i.e. flowering, pollination, fertilization).

5) Develop an integrated systems study designed to prepare a predictive model.

The investigation is comprised of eleven subprojects responsible for collecting data on organismic and community interactions with the final objective of predicting the ultimate effects on ecosystem structure and function (Miller and McBride 1975). The study hopes to develop a model that will identify important bioindicators for future use in determining the status of ecosystems of similar composition exposed to oxidant pollutants.

The Institute for Environmental Studies of the University of Wisconsin at Madison is documenting environmental change related to the Columbia Electric Generating Station. This study began in January, 1971, and has continued until the present. Specific objectives are outlined by Willard (1977):

1) detailed modeling of the flow of chemicals through a coal-fired generating station located in a wetlands ecosystem;

2) the impact of the generating station on the aquatic and terrestrial environment; and

3) the development of a data base and siting criteria protocol for future facilities already being planned.

Individual investigators and associates have been contracted to study a particular aspect of the surrounding ecosystem. The integration and synthesis of these studies is divided into four subprojects: Site Impact Study Data Management; Environmental Response Modeling; Public Interaction Workshops; and Site Analysis.

Integrated ecosystem studies of natural structure and function also provide helpful models for the development of a phytotoxicology monitoring program. The methods of analyzing community interactions and integrating independent studies are as useful for interpreting a system disturbed by pollutants as for interpreting "natural" ecosystem functions. The Hubbard Brook Ecosystem Study is comprehensive in its attempt to achieve a basic understanding of the structure and function of a northern hardwood forest (Likens and Bormann 1972; Bormann et al. 1974). Dahlskog et al. (1972) are conducting a multi-disciplinary research project on a boreal mountain-lake delta in Sweden. They are monitoring succession in a naturally unstable environment where plant species compositional changes occur over relatively short periods of time.

4.0. PROPOSED DESIGNS FOR A PHYTOTOXICOLOGY MONITORING PROGRAM

Two alternative proposals for a phytotoxicology monitoring program in northeastern Minnesota are outlined in this paper. The first alternative suggests the development of a fully-staffed research laboratory which would approach phytotoxicology in both a comprehensive and integrated manner. The second alternative would utilize investigator scientists who would conduct independent research.

4.1. Permanent Phytotoxicology Laboratory

The development of a permanent phytotoxicology laboratory is one option available to the State of Minnesota. The establishment of such a program would not only serve the state's people, but also facilitate the advancement of research in phytotoxicology. On an even broader scale, knowledge gained from a phytotoxicology laboratory would be of value nationwide as criteria for the establishment of biologically valid emission standards. Such a program would be most effective if initiated and integrated with statewide monitoring of air and water quality.

these are mutually exclusive?

4.1.1. Objectives

The objectives of a phytotoxicology laboratory would be three-fold:

1) The laboratory would be responsible for identifying areas of potential pollutant impact (e.g. copper-nickel mining) within the state of Minnesota. Long-term studies would be established in these areas including pre-operational, operational, and postoperational monitoring. The purpose of these studies would be to detect subtle alterations due to pollutants, to identify sensitive "indicator" species, to establish species toxicity levels, and to relate phytotoxic responses to air and water quality.

2) Experimental research would be conducted to complement field studies and to accomodate research problems that require manipulation of the ambient and edaphic environment.

3) The laboratory would respond to individual complaints when contamination by a pollutant is the suspected cause of damage to any type of vegetation.

4.1.2. Facilities

A phytotoxicology laboratory that is to monitor toxic responses of plants on a statewide level should coordinate closely with air and water quality monitoring projects so that results are integrated and related one to another. If the laboratory is to be multipurposed (i.e. respond to individual complaints, long-term monitoring of vegetation in areas of industrial development, experimental research, etc.) there is a need for office and work space and laboratory and greenhouse facilities.

4.1.3. Staff

A full-time phytotoxicology program would need to employ plant pathologists, plant ecologists, greenhouse, laboratory, and field technicians. Additional part-time summer help would be needed for field investigations. The number of people employed on a full-time appointment would depend on the scope of the program and the possible overlap in responsibilities of the positions.

4.2. Independent, Contract Monitoring

If the State of Minnesota does not establish a phytotoxicology laboratory there are alternatives for the more specific monitoring of copper-nickel mining activities. Minnesota has the unique opportunity to continue monitoring the region of proposed copper-nickel mining before mining activities commence. This opportunity must not be lost. One alternative would be to hire independent investigators on a contract basis to monitor different aspects of the vegetation for phytotoxic responses. This approach would make an integrated, holistic approach to understanding pollutant pathways a more difficult goal. However, with careful planning and cooperation among investigator scientists, valuable information could be synthesized for a smaller economic investment.

4.2.1. Objectives

The objective of this system of monitoring would be to understand phytotoxicity in northeastern Minnesota as related to copper-nickel mining. This goal would be accomplished by hiring scientists to investigate individual aspects of potential impact. The objectives would be very similar to those listed in the first portion of section 4.1.1. Long-term studies would be established in these areas including preoperational, operational, and postoperational monitoring. The purpose of these studies would be to detect subtle alterations due to pollutants, to identify sensitive "indicator" species, to establish species toxicity levels, and to relate phytotoxic responses to air and water quality.

4.2.2. Facilities

There would be no need for additional facilities, as the contract scientists would be expected to use their own laboratories.

4.2.3. Staff

The staff would be hired independently on a contract basis. The only full-time employee needed would be a person responsible for the hiring of, and the coordinating of the independent investigators.

4.2.4. Sponsorship

There are two alternatives for the sponsorship of independent contract monitoring. The state could assume responsiblity for organization and execution of the monitoring and funds could be gathered from taxes imposed on the mining company being monitored. The other option would be to allow the mining company to assume total responsibility for environmental monitoring. Theoretically, both alternatives would elicit the same results; however, there would be less potential for accusations of "conflict of interest" if the state were to administer the funds.

4.3. Establishment Considerations

The methods which could be utilized in a phytotoxicology monitoring program are as numerous as the alternatives for the design and organization of such a program. The techniques discussed in this proposal are examples of methods used elsewhere with proven effectiveness. It should not be interpreted that these are the only methods that have demonstrated reliability in monitoring phytotoxic responses. Together these methods form a comprehensive approach to understanding the response of vegetation to a polluted environment.

The decision to use a particular method must be based on its contribution to understanding pollutant pathways and resultant injury on an ecosystem level. Regardless of the type of monitoring program (i.e. permanent phytotoxicology laboratory or independent-contract monitoring) it is important to analyze all potential variables which might influence the degree of impact. Table 2 outlines the parameters to be sampled, the rationale for considering these parameters, and the methods which most effectively measure these parameters.

The methods discussed in this section were formulated using copper-nickel mining in northeastern Minnesota as an example of a potential pollutant source. However, if a statewide phytotoxicology monitoring program is instituted, the proposed guidelines and methods are designed to detect contamination by pollutants from any source.

4.3.1. Selection of Monitoring Sites

The selection of study sites for the monitoring of pollution impacts should be based on the following criteria:

1) Develop a careful understanding of the characteristics, needs, and desires of the proposed development.

2) Compile information specific to the area under consideration from data already available from the characterization of the Regional Copper-Nickel Study area.
   a) define dominant upland and lowland plant communities
   b) define habitats known to be particularly sensitive to pollutant injury
   c) define "critical" habitats--known to contain rare or endangered plants and animals
   d) use wind rose, dispersion models, and watershed maps to project the extent of influence of the proposed development

Same as 3a

3) Locate and establish study areas
   a) utilize wind rose, dispersion models, and watershed maps to define the areas most likely to suffer damage as well as control areas.
   b) define boundaries of area to be included in regional monitoring
   c) locate permanent plots in the dominant upland and lowland plant communities in both control and "impacted" areas
   d) locate permanent plots in "sensitive" and "critical" habitats if they are defined as something different than the dominant upland and lowland plant communities.

4.3.2. Regional Monitoring

In the selection of monitoring sites the boundaries of a large area, to be monitored on a regional basis, are defined. Identifying methods which are appropriate to large scale monitoring must consider cost and sampling time. Both aerial photography and lichen mapping are efficient, low-cost methods for assessing the extent of pollutant migration and contamination.

4.3.2.1. Aerial Photography

Aerial photographic techniques are becoming increasingly valuable tools for detecting both naturally-caused and human-induced pathological responses in vegetation on a regional scale (Wert 1969; Wert et al. 1970; Murtha 1972; Heller and Bega 1973; Boullard and Larcher 1974; Thorley 1975). Researchers have found that normal color and color infrared films are particularly valuable in detecting air pollution damage to forest trees. Subtle changes that can be easily overlooked on black and white films are discernable on color film (Thorley 1975).

A study by Wert (1969) of 100,000 acres of pine forest near Los Angeles used aerial photography and a statistical formula to estimate tree damage and resultant economic impact. This study found that combined small-scale and large-scale photographic coverage and sample ground plots provided an efficient means for monitoring a large area. The symptoms most valuable in identifying affected pines were color, low crown density, shortness of needles, and high frequency of bare branches (Wert et al. 1970). Damaged pine trees usually have only the current growth of needles, whereas healthy pines will retain needles up to five years. Tests were conducted during June, August, and December to determine which season would be most effective for detecting and evaluating damaged trees. It was discovered that the flush of green foliage from June to August masked the real condition of the trees (Wert et al. 1970). Thus, in California, December is the most desirable month for photographing the forest for phytotoxic symptoms.

A feasibility study of four different films and five scales found a combination of normal color film with a didymium rare earth filter and a scale of 1:8000 was most effective for identifying areas of affected trees (Wert et al. 1970). The same film type at a larger scale (1:1584) was found to be best for evaluating individual affected trees.

Blanel and Hocking (1974) used aerial photography to monitor forest decline in the vicinity of a nickel smelter in Thompson, Manitoba. Aerial reconnaissance demonstrated that discolored patches of forest decreased in frequency and intensity with distance from the smelter. Film types used were panchromatic black and white, color, and false-color infrared. Two different levels were flown, the lower yielding images at a scale of 1:20,000 (Fisher et al. 1977), has been monitoring the wetlands surrounding the Columbia Electric Generating Station near Madison, Wisconsin, by remote sensing. He is attempting to develop computer techniques for analyzing, displaying, and processing digital photographic data which would assess vegetative change in wetlands.

The use of aerial photography as a technique to monitor pollution is still a new field. The studies conducted indicate that aerial photography (using color film) is potentially an economical method for monitoring forest trees over a large area. To date this technique has not been able to detect previsual symptoms of disease. It is also unable to distinguish pathogenic responses caused by air pollution from those caused by pathogens endemic to the area. Because of this, preoperational photography is mandatory for the accurate assessment of copper-nickel mining impact. Repetitive photo coverage would offer forest pathologists a means by which to follow the development and expansion of any pathogenic response (Heller and Bega 1973). In addition, Meyer (personal communication 1977) feels that low-altitude aerial photography can provide detailed information for the long-term monitoring of permanent plots. He suggests that plots be permanently marked and photographed from a low-altitude (1200-1300 feet) at specified intervals of time. Color film aerial photography should be considered as a tool for both regional and site specific assessment of the impacts of copper-nickel mining.

4.3.2.2. <u>Lichens-Pollutant Indicators</u>

The known sensitivity of lichens to sulfur dioxide and their ability to accumulate heavy metals make them important pollution indicators (Skye 1968; Hawksworth 1971; Nieboer et al. 1972). By determining species present and their abundance, zones correlated to pollution levels can be quickly mapped.

The establishment of zones in this matter is one of the most rapid and economical methods for mapping the pervasiveness of pollutants on a regional scale. However, there are some limitations that should be recognized when using lichens as air pollution indicators. Within the boundaries of these limitations, lichens can serve both an important and unique role in monitoring environmental change.

1) Sulfur dioxide toxicity and lichen metabolism are not fully understood. To date, analyses for sulfur concentrations in lichens have poor reproducibility and limited accuracy (Tomassini et al. 1976). Thus, lichens cannot yet provide absolute measurements of sulfur concentrations. It is therefore proposed that lichens (species presence and abundance) be used only as indicators of general trends.

2) The sensitivity of particular lichen species has been correlated to actual levels of sulfur dioxide concentration by mapping species distribution in areas surrounding atmospheric gaging stations (Gilbert 1970, Hawksworth and Rose 1970). However, there is a danger in generalizing results from these studies to the same species in other geographical locations. Barkman (1958) found in a study of lichens of the Netherlands that species appeared to have different tolerances in different regions. It is thus necessary to determine the sensitivity of indicator species occurring in northeastern Minnesota.

3) Correlating species present with levels of sulfur dioxide concentrations is complicated by the wide range of factors influencing the toxicity of sulfur dioxide. Water retention properties, pH buffering capacities, pH of substrate, exposure to wind, and shadiness of the lichen's microhabitat are some of the variables that must be considered (Skye 1968, Gilbert 1968). Thus, as many variables as possible must be controlled when conducting a study.

Lichens can best serve a monitoring program as broad, general indicators of atmospheric pollution. It is proposed that the study area be mapped according to the distribution of certain indicator species. This map establishing the distribution of lichens in northeastern Minnesota should be annotated annually or at some established increment of time. The map will serve as a valuable indicator of subtle, accumulative atmospheric pollution. Hawksworth and Rose (1970) suggest that this method "provides a means of rapidly assessing, in a qualitative manner, the general levels of air pollution in an area without recourse to elaborate and expensive recording equipment." In addition, the indicator species should be analyzed at regular intervals for heavy metal accumulation by X-ray fluorescence (Nieboer et al. 1976).

Using data from atmospheric SO_2 and particulate monitoring stations placed in the study area, a scale could be developed correlating pollutant levels with the distribution of certain lichen species. The sensitivity of particular species in Minnesota could then be determined. With this information, a scale, like those of Gilbert (1970) and Hawksworth and Rose (1970), could be made relating pollutant concentrations with species presence-absence.

Lichens should be collected and mapped according to their presence, coverage, and luxuriance. For each variable, a scale would be created and standardized for recording data (e.g. Hawksworth and Rose 1970; LeBlanc and DeSloover 1970). The area mapped must be large enough to include land outside of the anticipated sphere of mining influence. Selection of sites to be sampled should consider prevailing wind conditions and specifications of smelter stack(s)(see Copper-Nickel Study Deposition Modeling Program). As many variables as possible should be standardized to eliminate factors other than air pollution. For example, lichens should be collected from trees of the same species, growing in comparable situations, and of similar age and diameter.

The data accumulated should be plotted on maps and toxicity zones established. Numerical methods (i.e. the Index of Atmospheric Purity) could be used, although many authors (Hawksworth 1970; and Saunders 1970) feel they are too time-consuming and appear to give no more accurate maps than zone scales.

The most reliable indicators are species which: 1) are uniformly distributed throughout area to be studied; 2) represent the different life-forms; 3) have been shown to be sensitive to the pollutants present; 4) demonstrate a range of sensitivities; and 5) can be easily recognized in the field. Dr. Wetmore has suggested that the following species are well distributed throughout northeastern Minnesota; Evernia mesomorpha (fruticose), Hypogymnia physoides (foliose), Parmelia sulcata (foliose), and Lecanora subfusca (crustose). These species represent a range of sensitivities and have been used in other studies. The validity of zone mapping increases with the number of species mapped; thus, four species would probably be the minimal number that should be used.

(Additional indicator species for northeastern Minnesota will be added to this list after Dr. Wetmore completes his study.)

The literature provides a clear estimate of both the potential for and the limitations involved in using lichens as pollution indicators. Thus, it is proposed that lichens be used as general indicators of pollution patterns and toxicity levels. During the summer of 1977 Dr. Wetmore completed a thorough study of species present in selected habitats of the Study area. The next step in using lichens as monitors would be to establish sampling criteria and map the area prior to the initiation of mining and processing of ore. Once lichen distribution has been established the response of lichens through time will provide an excellent bioassay system for monitoring the influence of industrial pollutants on plant growth.

4.3.3. Site Specific Monitoring

Permanent plots are to be selected according to the criteria outlined in section 4.3.1. It is important that the permanence of these plots is assured. Long-term monitoring is only effective if change is documented in the same location year after year. Measurements on the permanent plots must be initiated at least two to three years prior to the beginning of mining activities. Preoperational monitoring is necessary for the establishment of baseline data if results measured during the operational phase are to be accurately interpreted.

The fact that plots should be permanent and that their permanence should be assured is obvious. However, securing and "maintaining" undisturbed plots is very difficult. In seeking permanent plots for the monitoring of copper-nickel mining there are several possibilities that should be considered. The Keeley Creek Natural Area (Sec. 14, T61N, R11W) and the BWCA are both areas that have been already set aside on a permanent basis. Land for permanent plots in areas adjacent to mining activities should be reserved by the mining companies. If plots are needed in areas other than those already set aside or in land leased by the mining companies, negotiations should be made for state and federal lands.

The permanent plots should be measured following an established ecological sampling procedure. The objective of these procedures is to document both natural and human-induced changes in the structure and function of the habitats sampled. To monitor the floristic element of the terrestrial biota, the following parameters must be measured: 1) species composition-diversity, frequency, density, and dominance; 2) productivity/biomass; 3) nutrient cycling--rate of decomposition, and chemical composition, and 4) phytotoxic symptoms. The importance of monitoring each of these parameters and the methods by which these parameters may be assessed are outlined in Table (2). Sampling of these parameters should provide adequate data for a comprehensive analysis of the role of vegetation in a pollutant-stressed environment.

4.3.3.1. Standard Quantitative Plant Measurements

Standard quantitative plant measurements should be made (e.g. number of stems, stem diameter, height class, etc.) within the permanent plots. These measurements will provide data that can detect change in species composition, species diversity, productivity, and biomass over time. Detected changes in these parameters then can be interpreted in relation to existing environmental conditions, successional stage of the vegetation, and pollutant presence. Change in any of the parameters (i.e. loss of a species, replacement of one species by another)may be related to the species' particular sensitivity to the presence of pollutants or it may be related to a short-term prevailing environmental condition (i.e. drought) which is particularly stressful to this species.

Sampling methods are well documented in the literature (Braun-Blanquet 1932; Cottam and Curtis 1956; Goodall 1970; Shimwell 1971; Mueller-Dombois and Ellenberg 1974; Grigal and Ohman 1975). The four criteria used by the RCNS for choosing sampling methods are also valid criteria for methods to be used in an ecosystem approach to phytotoxicology monitoring: conventionality of methods, replicability of sampling procedures, field efficiency, and adequacy in describing small mammal and avian habitats (Operations Manual, RCNS). In addition, sampling methods should demonstrate adequacy in detecting stress in vegetation related to pollutant contamination.

4.3.3.2. Tree Radial Growth Studies

The value of annual ring widths for interpreting age of wood and for reconstructing past climates is well established (Douglass 1935; Fritts 1971). In recent years techniques have been developed for examining nonclimatic variations in widths of annual tree rings. There is increasing evidence that ring widths can be related to the presence of air pollutants.

Linzon (1966) found in his increment boring studies of white pine that trees growing in areas adjacent to smelters showed a gradual decline in the size of annual growth rings, whereas a constant pattern was maintained in other areas. Westman (1974) estimated change in growth of annual rings of spruce and pine in Sweden by using growth quotients and multiple regression analysis. The results indicated that emissions from a sulfite plant caused reduction in growth up to a distance of 10 km. A new technique for identifying nonclimatic variations in ring widths has been developed by Nash, Firtts, and Stokes (1975). An adjustment for variations due to regional climate is made for each tree core.

Several radial growth studies have been conducted in Minnesota and adjacent states. Kotar (manuscript) found reduction in the growth of balsam fir and white spruce in the vicinity of a copper smelter near White Pine, Michigan. However, trembling aspen, considered by many sources to be quite sensitive to SO_2 contamination, showed no reduction in growth regardless of the distance or direction from the smelter. A radial growth study of white pine being conducted by D. Grether for the Allen S. King Generating Plant of Stillwater, Minnesota, has to date found no correlation between decreased growth and proximity to the generating plant (Grether Annual

Report 1975). The results from a study of red pine radial growth in the vicinity of the Clay Boswell Station at Cohasset, Minnesota (MPCA 1977) indicated that emissions from the plant have not significantly affected the growth rate compared with other influencing factors.

4.3.3.3. Decomposition Studies

Decomposition is an essential process governing the rate of element cycling in terrestrial ecosystems. Soil micro- and macroflora and fauna are important contributors to the decomposition of litter in forests, and heavy metals pollution has been shown to restrict the activities of these organisms (Bond et al. 1976, Tyler 1975a and 1975b, 1976). When decomposition rates are reduced, essential nutrients are bound in accumulating litter, and, ultimately, production of the ecosystem as a whole is decreased.

Change in the rate of decomposition can be determined by several different methods. Some involve sophisticated, expensive machinery (e.g. CO_2 evolution determinations utilizing respirometers) while others require only simple weight measurements (e.g. litter bags).

Rühling and Tyler (1973) compared the decomposition rate of spruce needles, under controlled laboratory conditions, taken from sites surrounding two metal processing industries in Sweden. They found a significantly negative correlation between heavy metal concentration and CO_2 evolution rate. It was concluded that, in acid forest sites, the overall decomposition rate will be depressed even by moderate concentrations of heavy metal ions (Ruhling and Tyler 1973). Friedman, at the University of Toronto, is studying effects of heavy metal pollution on decomposition of aspen leaves in the Sudbury, Ontario, area. He encloses leaves, collected in the spring, and carefully dried and weighed, in bags made of fiberglass screening. These bags are deposited in the field and then retrieved throughout the growing season. After drying, litter is reweighed and weight loss over time is calculated. The RCNS has conducted a comparable study during the summer of 1977 in six aspen stands located in the RCNS area. Thus, baseline decomposition data are available for six sites (see Litter Decomposition Studies, RCNS 1978).

4.3.3.4. Chemical Analysis of Plant Tissue

Chemical analysis of plant tissue is one method for assessing the role of vegetation as a sink for air and water pollutants. It is also important if included in a broader program for determining where nutrients are being held in the system and if nutrient cycling is being altered by functions of the vegetation. Background levels for the Regional Copper-Nickel Study area have already been assessed (see Chemical Analysis of Vegetation, RCNS 1978). However, background levels will need to be determined for each permanent plot.

Sampling methods for chemical analysis of vegetation are well discussed in the literature (van den Driessche 1972, 1974; Everard 1973; Krupa 1977; RCNS 1978). There are many variables to consider when sampling the vegetation: structural position of species within the habitat, age of foliage, time of year, nutrient availability, competition, and micro- and macroclimatic variations (van den Driessche 1974). Methods should be designed to sample both spatial (variation between stands of a given species) and temporal (variation within a stand occurring from month to month over the growing season) variation (Krupa 1977).

In Sweden, sulfate was estimated in leaf samples (mostly birch) to map SO_2 pollution around SO_2 emitting industries (Lihnell 1969). Diagrams based on sulfate determinations are related to distance from source, prevailing wind conditions, annual variations, influence of change in industrial activity, and the interaction between several associated sources of pollution. Lihnell found a positive correlation between sulfate diagrams and the diagrams illustrating reduction in growth of forest trees of the same area. "Altogether, the results support the assumption that, at least under certain conditions, sulfate analysis in tree leaves gives a reliable picture of SO_2 pollution" (Lihnell 1969). Balsillie et al. (1975) found heavy metal contamination in their analysis of vegetation surrounding a zinc plant in Ontario, Canada. Their results show that levels of copper, iron, lead, and zinc are significantly different in a zone extending 3 km northeast of the zinc plant. A similar study was conducted by the Ministry of the Environment in an area surrounding Algoma Steel Corporation's plant at Wawa, Ontario. Levels of sulfur, iron, and arsenic decreased with increased distance from the sinter plant (McGovern 1975).

The full potential for using results from chemical analysis of vegetation, as an indicator of pollutant contamination, has not yet been realized. The dimensions of this potential are greatly increased with concomitant sampling of the soil. However, if any of these results are to be correlated in a valid manner to pollutant presence, background levels must be established prior to mining operations.

4.3.3.5. Plant Pathology Studies

A surveillance study to determine the endemic occurrence of insect, disease, oxidant, and physiological injuries on vegetation must be conducted before operational activities begin (Linzon 1972). Plant specimen should be collected for a reference herbarium and diseased plants documented by photographs. It is important that this assessment be conducted for several years prior to operation of mining. Sampling should occur monthly or at least several times during the growing season. Once the presence of naturally-occurring plant pathogens is established, reconnaissance for natural pathogens can become part of an on-going monitoring program for the detection of incipient plant injury of any cause.

Some studies (Tibbitts 1977; Balsillie et al. 1975) select particular species and monitor the occurrence of natural and human-induced pathological symptoms both in the preoperational and operational phases. The Institute for Environmental Studies of Madison, Wisconsin, is studying plant damage related to the Columbia Electric Generating Station by monitoring indicator species: alfalfa, a major crop species of the area; and blackberry and ragweed, both abundant in the area. Data were collected before operation of the generating plant began and has continued during each growing season. Alfalfa was sampled at sixteen sites at three different times: early June, late July, and late September. The sites were located approximately 3, 5, 8, and 16 kilometers west, northeast, southeast, and southwest of the station (Tibbitts 1977). Balsillie et al. (1975) of the Ministry of the Environment developed a program to monitor air quality, vegetation, and soils two years prior to the scheduled opening of a zinc plant. Ten study plots within 32 km of the plant and two control plots each 80 km from the plant were established. Twenty trembling aspen trees and ten shrubs (selected from either alder, hazel, mountain maple, or choke cherry) were tagged. These plants are observed on a monthly basis throughout the growing season.

A different approach is to monitor all species within the boundaries of established plots (Krupa 1976; MPCA 1977). The pathology study conducted at the Clay Boswell Station near Grand Rapids, Minnesota, surveyed all species within the permanent plots. A listing was made of the species exhibiting pathological symptoms and color photographs were made to confirm the field notes. Two plant pathologists independently surveyed and evaluated the incidence of disease. Estimates based on their observations were averaged and a percentage of the number of plants affected in the plot was established (MPCA 1977).

It is suggested, for the phytotoxicology monitoring program in Minnesota, that all species within the established permanent plots be monitored for visible injury. It may be desirable to select particular species (following the methods of Balsillie et al. 1975) that are known to be sensitive to pollutants and monitor their development more closely. However, a comprehensive survey is the only method that documents the response of all species and allows for the discovery and identification of new indicator species.

4.3.4. Experimental/Bioassay Monitoring

Regional and site specific long-term monitoring are both essential to the understanding of phytotoxicology. However, some plant processes need to be monitored in a controlled environment or with the assistance of laboratory equipment. Guderian (1977) feels that there are three different procedures that should be considered for experimental research:

investigations in the laboratory and in controlled-environment chambers, under glass or in plastic greenhouses in the field, and investigation of test plants near sources of pollution.

The first procedure, experiments conducted in controlled-environment chambers, allows for the investigation of the effects of single variables or the synergistic effect of many variables. Guderian (1977) describes the mechanics and potentials of a system he developed. The phytotoxicology section of the Ontario Air Management Branch also has developed specially modified controlled-environment plant chambers for air pollution work. Synthetic pollutants, singly or in mixtures, are injected into the chambers and the effects on various plant species are determined under varying environmental conditions (Linzon 1970). The second procedure, fumigation experiments in the field, tests the response of plants to existing levels of pollutants and allows for the isolation of some plants from fumigation. Alternatively, naturally growing plants can be fumigated with known levels of pollutants. The third procedure studies the response of the test plants near the source of pollution. This method involves placing plants of varying sensitivities in pots in areas adjacent to the polluting industry.

These three procedures are representative examples of the type of experimental design that could be developed for determining close-response relationships. Results from controlled-environment studies complement data gathered from long-term field monitoring.

4.3.5. Analysis-Impact Assessment

Analysis and impact assessment should take place on a regular basis throughout the duration of long-term monitoring. The value of phytotoxicology data is directly related to the insight it provides for understanding the implications of chemical, physical, and other biological measurements. Isolated measurements are only significant when related to the ecosystem as a whole. A summary of the factors that are to be identified and defined by integrating data are outlined in Figure 2.

5.0 CONCLUSION

> Living organisms can serve as excellent quantitative as well as qualitative indices of the pollution of the environment. Plants and animals are continually exposed and can act as long-term monitors that integrate all environmental effects to reflect the total state of their environmental milieu. They can show the pathways and points of accumulation of pollutants and toxicants in ecological systems. Their use can remove the extremely difficult task of relating physical and chemical measurements to biological effects (Thomas et al. 1970).

That pollution exists in today's world is a fact. Air and water quality are currently being monitored across the nation. The far-reaching implications of these measurements become obvious only as we gain insight into the response of biological organisms to a toxic environment. This proposal is concerned with the floristic element of the biota. It explains the justification for and the considerations involved in the design of a phytotoxicology monitoring program.

Plants are potentially indicators of toxicity levels, low-level contamination, and ecosystem alterations caused by pollutants. There is little precedent in the United States or elsewhere for the establishment of a phytotoxicology program. Two alternative designs are suggested, a permanent phytotoxicology laboratory and independent-contract monitoring. Monitoring techniques were selected that could be utilized in either design. Comprehensive monitoring should include methods which sample the area on a regional scale (e.g. aerial photography, lichen mapping), in permanent plots (e.g. quantitative measurements, plant pathology studies, etc.), and by use of experimental research (e.g. bioassay studies). Data gathered from these studies should be integrated with physical, chemical, and other biological measurements so that a holistic approach is possible in the analysis and impact assessment phase of monitoring.

Environmental monitoring has traditionally been biased towards the measurement of abiotic factors. Detailed knowledge of the composition and changes in the soil, water, and atmosphere and their contaminants are relatively useless unless we understand their effects on biological organisms , Quantifying the effects of physical and chemical environmental factors is necessary if air and water quality standards are to be effective. Thus, the study of symptomatic expression of plants to a contaminated environment is essential if we are to understand the immediate and long-range impact of copper-nickel mining in Minnesota [is to be understood].

Figure 1. Phytotoxicology monitoring.

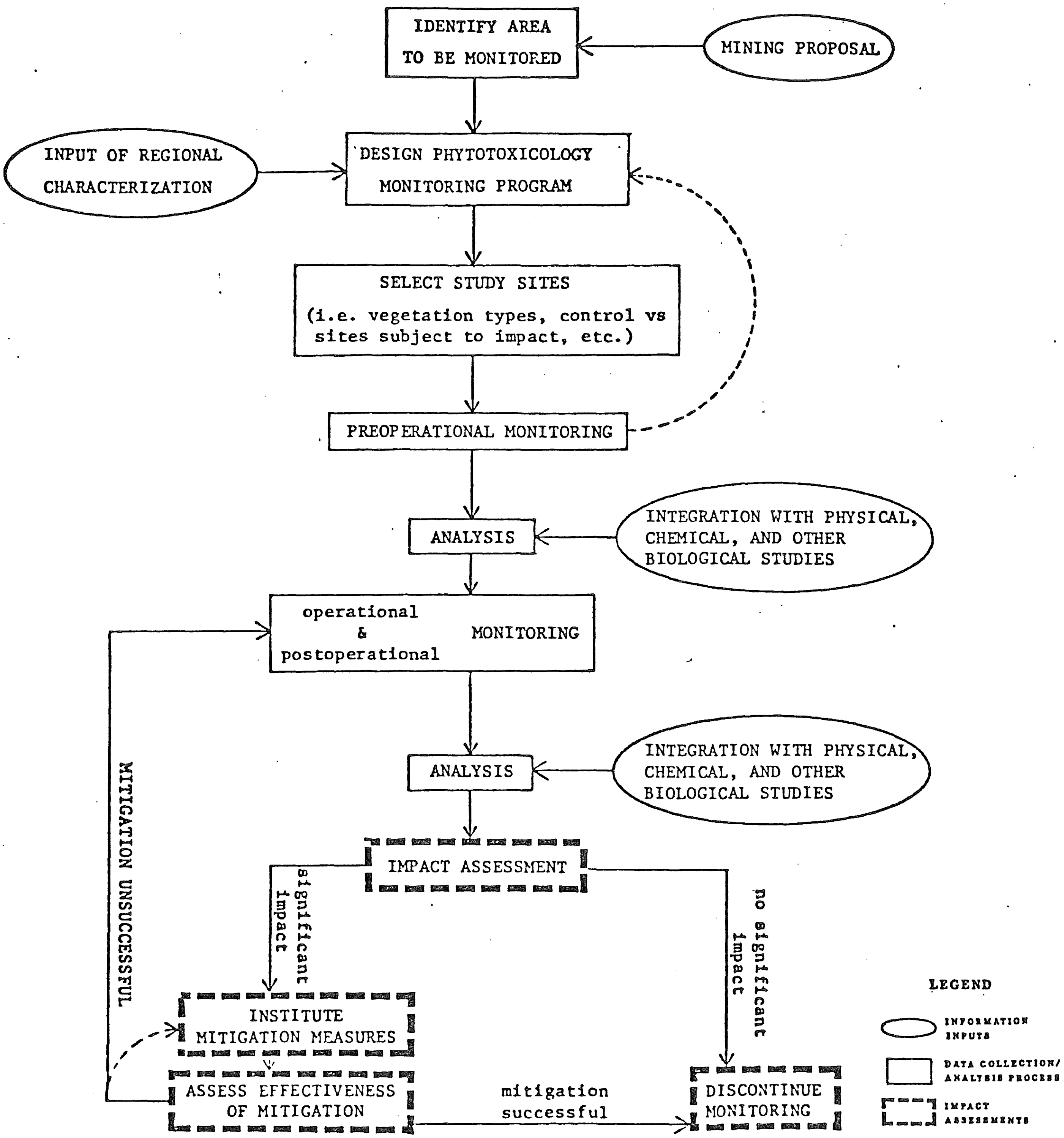

Figure 2. Analysis-Impact Assessment

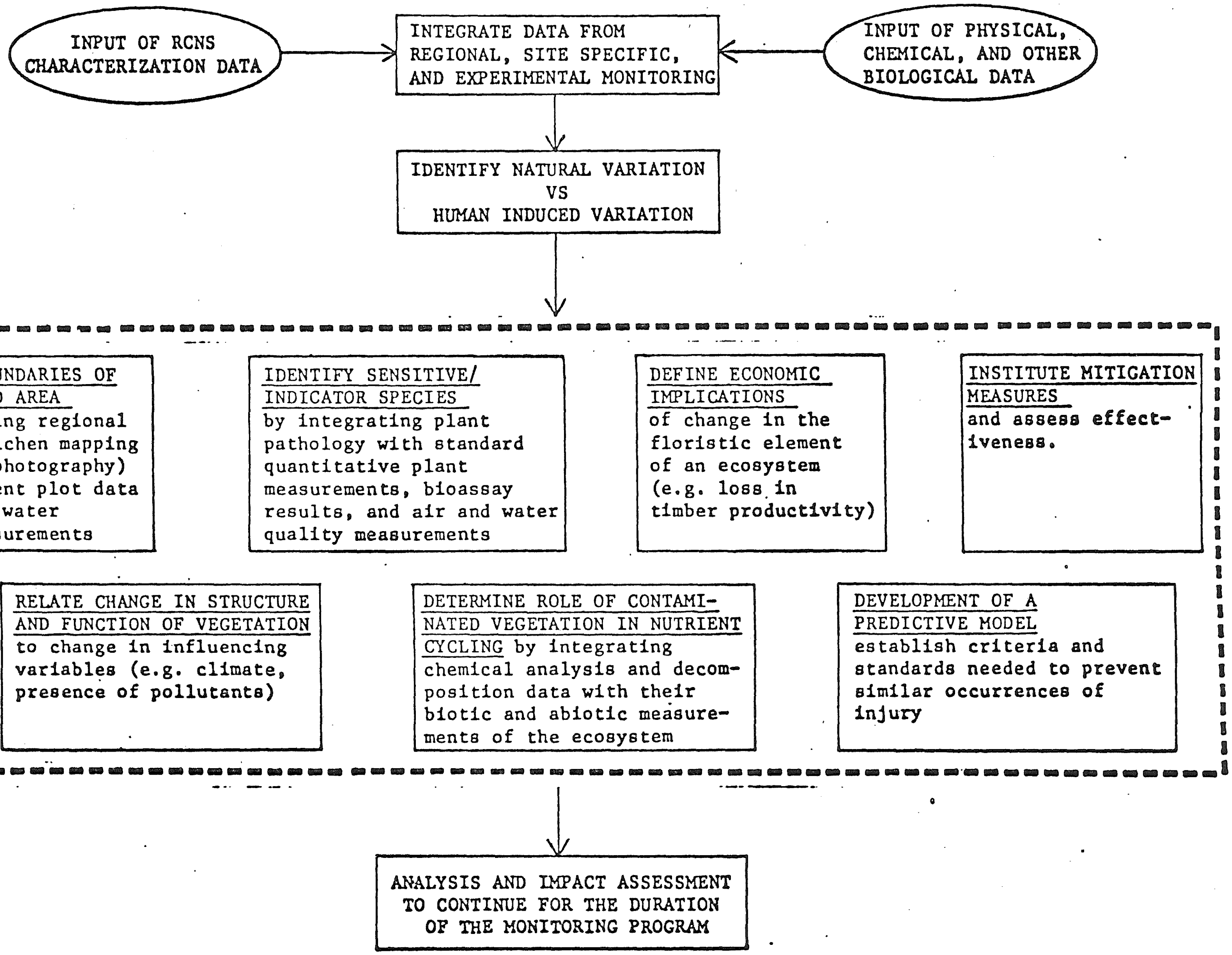

Table 1. Influence of air pollution on temperate forest ecosystems.

DESIGNATION	AIR POLLUTION LOAD	RESPONSE OF VEGETATION	IMPACT ON ECOSYSTEM
Class I	Low	1. Act as a sink for contaminants.	1. Pollutants shifted from atmospheric to organic or available nutrient compartment
		2. No or minimal physiological alteration	2. Undetectable influence, fertilising effect
Class II	Intermediate	1. Reduced growth a) detruded nutrient availability (i) depressed litter decomposition (ii) acid rain leaching b) suppressed photosynthesis, enhanced respiration	1. Reduced productivity, lessened biomass
		2. Reduced reproduction a) pollinator interference b) abnormal pollen, flower, seed, or seeding development	2. Altered species composition
		3. Increased morbidity a) predisposition to entomological or microbial stress b) direct disease induction	3. Increased insect outbreaks microbial epidemics Reduced vigor
Class III	High	1. Acute morbidity	1. Simplification; increased erodibility, nutrient altered microblimate and hydrology
		2. Mortality	2. Reduced stability

SOURCE: Smith, 1974.

Table 2.

PARAMETERS TO BE SAMPLED		RATIONALE FOR CONSIDERING THESE PARAMETERS		METHODS
Species Composition Diversity Frequency Density Dominance	→→→→→→→	Detect Change in Ecosystem Structure and Function (i.e. loss of species, replacement of one species by another, stunted growth...)	→→→→→→	Aerial Photography Lichen Mapping Detailed Plot Mapping Standard Quantitative Plant Measurements (i.e. stem diameter, no. of stems...)
Productivity/Biomass	→→→→→→→	Detect Change in Ecosystem Structure and Function (i.e. stunted or increased growth) Economic Implications of Change in Productivity/Biomass (i.e. loss in timber productivity)	→→→→→→→	Standard Quantitative Plant Measurements Tree Radial Growth Studies
Nutrient Cycling Rate of Decomposition Chemical Composition	→→→→→→	Detect Change in Flow of Nutrients (i.e. role of vegetation as sink for pollutants, effect of pollutants on decomposition processes...) Detect Change in Transfer vs Compartment Functions	→→→→→→→	Litter Bags Chemical Analysis of Plant Tissue
Phytotoxic Symptoms	→→→→→→→	Establish Endemic Occurrence of Plant Pathogens Recognize Pathological Responses Due to Toxic Pollutants	→→→→→→→→	Plant Pathology Surveillance Bioassay (controlled-environment studies) Qualitative Measure of Health and Vigor of Plants

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