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Nutrient Limitations and Fertilization

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Historical Background

While the benefits of applying manure to land has long been appreciated the idea of a plant nutrients probably only dates from 1727 when Stephen Hale noted that 'we find by chemical analysis of vegetables, that their substance is composed of sulphur, volatile salt, water and earth.' Despite observed growth responses of plants to compounds such as saltpetre (a nitrate salt), Epsom salts (magnesium sulfate), and phosphates, further advance in the understanding of plant nutrition was stymied by the widespread acceptance of the idea of Wallerins that humus itself was the fundamental source not only of nutrients but also of carbon. Progressively this came to be questioned and in 1845 Liebig, on the basis of calculations of the yield of carbon as wood and agricultural produce from nonmanured land, concluded that 'it is not denied that manure exercises an influence upon the development of plants; but it may be affirmed with positive certainty, that it neither serves for the production of carbon, nor has any influence on it.'

Building upon the work of Liebig, chemists such as Bossingault in France and Lawes and Gilbert in Britain weighed and analyzed manure and plants to construct early nutrient input–output balance sheets for a range of agricultural crops. Bossingault's data were used by Ebermayer in 1882 to compare nutrient accumulation in forest stands with that in agricultural crops. Earlier Ebermayer had been the first to diagnose nitrogen (N) deficiency in trees in Bavaria on sites that had been degraded by long histories of litter removal for animal bedding and other agricultural purposes. Despite this new understanding, foresters of a century ago seldom showed much interest in tree nutrition, being able to turn to the work of Dengler who had demonstrated that the nutrient requirements of a closed-canopy forest stand were on average only about one-twelfth of that of agricultural crops. Indeed, in his silvicultural textbook of 1904 Schlich enunciated the orthodoxy of his time when he stated that 'almost any soil can furnish a sufficient quantity of mineral substances for the production of a crop of trees, provided the leaf mould is not removed.' This sentiment was echoed by Baker in his book of 1934, for long one of the standard silvicultural texts.

Despite this complacency, at the start of the twentieth century foresters in Belgium, and later in Ireland and Scotland, were finding that trees newly planted on poor soils could show dramatic growth responses by application of the phosphate-containing basic slag (thomasphosphat) and some responses to wood ash application were reported from the Nordic countries (probably a response to potassium (K)). Similarly, in both Australia and New Zealand growth of the new forest plantation were found to be dependent on the application of phosphorus (P). In South Australia trees sometimes failed even where P had been applied until it was noted that those grown adjacent to galvanized wire fences were better than those distant from them, and so zinc deficiency was identified. In the decades that followed, forest scientists from many of the countries with large afforestation programs have identified deficiencies of one or more of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), and boron (B) in young plantation trees. Calcium (Ca) deficiency has been confirmed in the nursery but the few reports of deficiencies of this element in the forest remain rather unconvincing. Additionally, by the middle of the twentieth century reports were also coming in of nitrogen deficiency in older coniferous forests in the boreal regions of Europe and North America.

Nutrient Cycles and Fertilizer Need

The study of nutrient cycling in forests of various ages has provided the explanations to a number of the conundrums posed by early work on fertilizer responses. The cycles within a well-established forest are characteristically very tight, that is there is efficient reuse of nutrients, largely through recovery (retranslocation) of nutrients from dying organs, notably leaves before they are shed, and through the efficient capture by roots and mycorrhizae of nutrients released through decomposition of litter. **Table 1** shows that retranslocation from foliage can contribute a quarter to half of the N, P, and K needed for new growth, and various studies suggest that the contribution from the decomposition of litter fallen from the same trees is not dissimilar (although with a lag phase for the time decomposition takes). The net consequence of this efficient recovery is that in a closed canopy forest, in which the amount of leaves produced annually is more or less equal to the amount dropped, the demand on fresh supplies of nutrients from the soil can be quite low. The position prior to canopy closure, however, when the both the green crown and the fine root biomass (both of which contain high concentrations of nutrients) are expanding the contribution internal cycling or litter decomposition can make to nutrient demands is limited and so a greater contribution has to come from the soil reserves (**Table 2**). Even though the total nutrient demands by the young trees are less than those of the older trees, the latter are asking much less of the soil reserves. Thus, the picture is one of high demands on soil reserves when a young crop is establishing its canopy, a demand that relaxes thereafter as the contribution from nutrient cycling increases. It is therefore, not surprising that nutrient deficiencies were seldom encountered until the twentieth century expansion of plantations onto poor ground.

As a forest ages further, if it is not harvested it starts to break up and growth declines while mortality increases. Uptake of nutrients may then become less than the release on decomposition and nutrients start to be lost from the site. However, prior to this stage in the coniferous forests of the boreal region the slow decomposition of litter can lead to such an accumulation of humus that an unacceptable proportion of the nitrogen capital of the site becomes locked up, the supply of available nitrogen progressively declines, and the trees start to show nitrogen deficiency. This seems to be the explanation for N fertilizer responses in areas such as Sweden, Finland, Canada, northwestern USA, and mountain forests in central Europe. The industrial importance of such forests has meant that considerable research effort has been devoted to them, contributing to the belief that N is the nutrient most commonly limiting in the forests of the world. However, this accolade should probably be given to P.

Because of the importance of nutrient retranslocation in nutrient cycles, anything that causes major loss of green foliage (i.e., before nutrients can be retranslocated back into the tree) can cause a short-term reappearance of any nutrient deficiency previously seen in youth. Such events include hail damage, insect damage, or even removal of trees in thinning. When a forest is thinned a significant proportion of the green foliage is deposited on the forest floor and the nutrients within it can no longer be accessed in the short-term through retranslocation. They will only become available in the medium term through mineralization on decomposition. Meanwhile, the remaining main crop trees have to fill the gaps that have been created in the canopy without recourse to the nutrients in the leaves that previously occupied these spaces. Their own internal supplies, coupled with whatever is available to the roots, may now be inadequate and deficiencies occur. Indeed, a positive interaction between thinnings and fertilizer application has often been recorded in situations where unthinned stands show no fertilizer response.

Table 1 Estimates of the contribution to nutrient demands by new growth that are met by retranslocation from old foliage prior to abscission

Species	*Age (years)*	*Percentage of nutrient requirement*		
		N	*P*	*K*
Pinus taeda	20	39	60	22
Pinus sylvestris	15	30	23	19
Pinus sylvestris	46	55	64	57
Pinus sylvestris	100	41	34	27
Pinus nigra	40	50	57	58
Abies amabilis	175	54	59	38
Mixed deciduous	Mature	54	25	15
Mixed deciduous	Mature	79	74	41
Eucalyptus obliqua	Overmature	34	46	28

Table 2 Sinks and sources (kg ha^{-1} year^{-1}) of nitrogen (N) and potassium (K) in young (2-m tall) and old (11-m tall) stands of *Pinus nigra*

	Nitrogen		*Potassium*	
	Young	*Old*	*Young*	*Old*
(1) Total required for new growth	66	138	29	66
(2) Supplied by retranslocation	11	69	7	38
(3) Taken by roots (i.e., 1 – 2)	55	69	22	28
(4) Available from litter decomposition[a]	7	39	1	16
(5) Uptake from soil reserves (i.e., 3 – 4)	48	30	21	12
(6) Net annual accumulation in trees	45	18	18	11

[a] Decomposition of litter fallen from current crop of trees only, release from pre-existing organic matter considered as being from soil reserves.

Predicting and Diagnosing Nutrient Deficiencies

The occurrence of nutrient deficiencies varies with the age of stand, soil type, and to some extent with species. Clearly, the forest manager needs to be able to diagnose a deficiency should this occur and, preferably, be able to predict what ameliorative treatment may be required. Four options are available; diagnosis on the basis of visual crop symptoms, diagnosis on the basis of soil analysis, diagnosis on the basis of tissue analysis, and prediction on the basis of some characteristic feature of the site.

Visual Symptoms

The various nutrients play specific physiological roles and if present in insufficient quantity disorders result which can lead to diagnostic visual symptoms. There is some variation between species, particularly between conifers and broadleaves, but general symptoms are as shown in **Table 3**. Because, these visual symptoms can be misleading, they are usually confirmed by foliar analysis.

Soil Analysis

Soil analysis has proved to be very useful in both agriculture and horticulture. In the forest, however, soil analysis has seldom proved to be of consistent value. In part this is because the perennial roots of trees, together with their mycorrhizae, seem able to access forms of nutrient elements not accessible to short-lived arable plants so the chemical soil extractants developed for agriculture may not be appropriate. Perhaps more significant, however, is that over time tree roots can exploit all the rooting volume available to them. This volume can be very variable between sites, often more variable than the quantities of available nutrients per unit volume (in agriculture and horticulture rooting is essentially consigned to the uniform depth of the plow layer). At all events, soil analysis in forestry has only proved most useful over limited areas where rooting volume is not a variable, such as glacial outwash plains, volcanic ash, or extensive areas of loess.

Table 3 Visual symptoms of nutrient deficiencies

Nutrient	*Symptoms*
Nitrogen (N)	Needles or leaves are small and pale green turning yellow throughout the crown but most severe on young foliage
Phosphorus (P)	Reduced needle or leaf size and an exaggerated if rather dull green color; in extreme cases a brownish tinge may develop and buds towards the top of the tree may die
Potassium (K)	A pale straw-yellow color that appears first on needles at the tips of current shoots or leaf margins; color may develop to a pinkish brown and is often more severe in winter
Magnesium (Mg)	Golden yellow discoloration of needle tips or of irregular blotches on broadleaves; this is more pronounced on upper parts of the tree and in autumn
Copper (Cu)	Little change in leaf size or color although there may be dark blotches on broadleaves; branches droop and leading shoot is very sinuous or even pendulous
Boron (B)	Death of buds and shoots, particularly after growth has commenced in summer; problem most pronounced on leading shoot and as tree dies back it becomes very misshapen; pith in shoots may show brown necrosis

Foliar Analysis

Analysis of almost any living tissue will give an indication of the nutrient status of a plant; however, foliage has consistently proved to be the most useful for this purpose. Nutrient concentrations in foliage vary both with position in the tree and with age of the leaf. Generally, the physiologically active nutrients increase in concentration up the tree, as illumination increases, although Ca usually shows the reverse trend. Some authorities have advocated using lower crown foliage on the grounds that it is from these that any nutrient under stress would be removed first. However, the position of the lower crown varies with stocking density so it is difficult to standardize and ensure comparability. The effect of age on nutrient concentrations is shown in **Figure 1**, emphasizing the need to standardize the time of sampling. These considerations have led most forestry organizations to standardize sampling such that for conifers current fully formed needles (usually sampled around October in northern regions and April in southern regions) are taken from the top whorl in high latitudes or the top three whorls in lower latitudes, whereas samples from broadleaved trees are taken from the upper third of the crown (ensuring full illumination) in August in northern latitudes or February in Southern latitudes.

The theoretical dependence of growth on nutrient concentration is shown in **Figure 2**. The optimum on this curve can be a well-developed turning point, which is usually the case for N, P, and K, or it can take the form of a long plateau, which is typically the case for Cu and particularly Mn. Along this plateau the plant is taking up increasing amounts of a nutrient without showing any change in growth. Uptake over this range is often referred to as ‘luxury

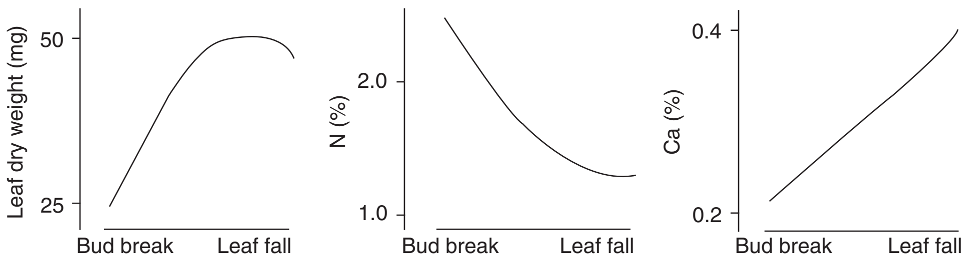

Figure 1 Changes in leaf dry weight and concentrations on nitrogen and calcium through the growing season from bud break to maximum leaf fall for a conifer such as pine.

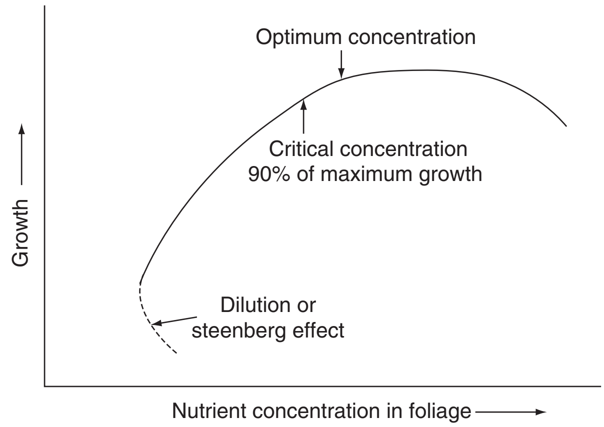

Figure 2 Generalized relationship between growth and foliar nutrient concentration.

Table 4 The foliage concentrations of nutrients below which tree growth starts to decline. These are values for young trees in the forest (*c.* 0.5–4.0 m tall) at the time when nutrient problems are most likely; for younger and perhaps older trees somewhat higher concentrations are necessary

Nutrient	*Evergreen conifers*	*Broadleaves and deciduous conifers*
Nitrogen (N)	1.50%	2.20%
Phosphorus (P)	0.14%	0.20%
Potassium (K)	0.50%	0.90%
Magnesium (Mg)	0.10%	0.10%
Boron (B)	8 ppm	ND
Copper (Cu)	2 ppm	ND

ND, no adequate data.

uptake,' although (as will be discussed later) this is a rather misleading concept in the case of perennial plants such as trees.

One factor that has to be kept in mind when using foliar analysis is that at least for N, and probably for the other major nutrients, the optimum concentration does shift with age of the tree. It is usually high in young seedlings but the declines as the tree becomes established, thus optimum N for seedling pine is about 3% but by the time the tree has reached a height of 2 m may be only 1.5%, rising to around 2% in a closed canopy crop. Suggested optimum concentrations are shown in **Table 4**.

Because the growth response to a fertilizer applied nutrient at the upper part of the curve, just below the optimum point, is small the concept of a critical nutrient level, usually 90% of the optimum, has been introduced. Below this critical level fertilizer responses may be worthwhile but above it not so.

When diagnosing on the basis of foliar analysis, results are presented as a concentration, that is the ratio of the weight of an element present to the weight of the leaf. Changes above or below the line will result in a change of concentration. For example, if a pollutant gas is reducing carbohydrate production this will be accompanied by an increase in concentration of nutrient elements without there having been any increase in nutrient uptake. Similarly, if growth is being reduced by a severe deficiency of one element, say P, other elements may appear to be present in adequate amounts. If the deficiency is alleviated by the application of the appropriate fertilizer a secondary deficiency of another element may be revealed the supply of which was sufficient when growth was restricted but not so after the restriction is removed.

Caution has to be exercised when interpreting foliar analysis and if time is available a small trial to confirm the diagnosis is often advisable. In Canada, a short cut has been devised, 'trajectory analysis,' whereby fertilizers are first applied and then the response measured in terms of needle weight and nutrient concentrations to determine which element, if any is deficient. This has some advantages in reducing the time to gain a diagnosis but is unlikely to be as accurate as more conventional approaches. If carefully used the straightforward use of concentrations of individual nutrient, coupled with sensible assessment of the site and, if need be, a confirmatory trial, remains the best approach.

Site Characteristics

Site as classified by one or more of soil type, geology, and ground vegetation can give a very good indication of whether any particular nutrient deficiencies might be anticipated. This is particularly valuable when creating a plantation on bare land. Of course such classifications will differ between bioclimatic regions but many forest services have developed classifications, or lists of indicator plants, based largely on experience, to predict future fertilizer needs if any. Such an approach has the great advantage of enabling advance assessment of the costs that might be incurred in plantation creation.

Effect of Species

As previously discussed, once a forest crop has closed canopy nutrient demands decline. The only continuing net accumulation is in the biomass of wood. Concentrations of nutrients in wood are low and usually do not differ much between species. Differences in nutrient demands reflect differences in growth rate of wood such that a linear relation can be demonstrated for this stage between uptake of N and P and mean annual increment. Prior to canopy closure, however, the situation is different for different species will develop very differing amounts of foliage in these early years. Generally, deciduous tree carry 3–6 tonnes ha^{-1} of foliage, pines some 6–12 tonnes ha^{-1}, and the white wooded conifers (spruces, firs, Douglas-fir, hemlock, etc.) 10–20 tonnes ha^{-1} of foliage. Differing amounts of nutrients, therefore, will need to be found in the early years of the rotation to develop the canopies of these trees to the stage when nutrient cycling will cover much the nutritional needs of the new leaves produced each year. This early difference is illustrated in **Table 5**.

Such a model produces the intuitively sensible prediction that spruces are more nutrient-demanding than pines. It also predicts that oak is less nutrient-demanding than either of them which does not concur with their known site requirements, oak usually requiring much more fertile soils. This introduces an important distinction between 'nutrient demands' and 'site demands.' Nutrient demands differ among species because of the amount of foliage they initially need to accumulate and, thereafter, because of differences in volume growth. Site demands, by contrast, reflect not only differences in nutrient demand but also the ability of the roots and associated mycorrhizae to obtain nutrients from intractable soil sources. Pine is good at this, oak is poor.

Table 5 Rate of change in weight of foliage carried with age for even-aged stands of pine and spruce at comparable locations

Age period (years)	*Increase in weight of foliage (tonnes $ha^{-1}year^{-1}$)*	
	Pine	*Spruce*
0–10	+0.2	+0.5
10–15	+0.4	+1.0
15–20	+0.8	+1.4
20–25	+0.2	+0.2
25–30	−0.1	−0.3

Use of Fertilizers

As a result of a desire to minimize the use of chemicals in forests, application of fertilizers is considered a remedy of last resort. Whereever possible, other approaches should be considered, notably selecting a species better suited to the site. Sometimes, however, this option may not be possible, either because the trees are already established or the soil is extremely nutrient deficient, as may be the case in nonnatural soils such as mine waste. In such cases fertilization is necessary.

Forms of Fertilizers

A wide choice in chemical forms of fertilizers is available. The decision of what to use is in part a function of ease of application and application cost, so urea which is 46% N has attractions over ammonium sulfate at 21% or ammonium nitrate at 35% because the cost of application is lower per unit weight of N. Availability is also important and so choice is often dictated by what is being used in agriculture.

In Finland and Scandinavia concern that rainwater acidity might accelerate soil leaching, or that N inputs in polluted rain might lead to 'unbalanced' nutritional conditions, has led to the development of complex mixed fertilizers ('reconditioning fertilizers') containing up to eight nutrient elements. In the medium to long term these may serve such a purpose but in the shorter term they appear to have no advantage over the application of the one or two elements known to be deficient. Acid rain has also led to a renewed interest in the application of lime to forests. Many thousands of hectares have been so treated but the advantages remain unproven. A vast number of liming trials have been carried out since the nineteenth century and these usually show no growth response, or even a short-lived depression. In a few cases, an eventual improvement in humus form has lead to better tree health but the response is long delayed and hard to predict.

Response to Fertilizers

If a nutrient deficiency is correctly diagnosed, application of an appropriate fertilizer will lead first to both a reduction in number of leaves shed and to an increase in photosynthetic efficiency of the leaves retained, and then to an increase in the number of leaves formed (this being the most important factor). Thus, by the second growing season the photosynthetic area will have been considerably increased leading to an increase in net primary production and so greater stem wood growth. Thereafter, the duration of the response is a function of the amount of the fertilizer nutrient the trees have been able to accumulate in their tissues. As shown in **Figure 3**, increasing the rate of fertilizer application may not lead to continuing growth rates in the years immediately after application but because more nutrient element might have been stored the response period will continue longer.

Only a portion of the added fertilizer nutrient is used by trees. A major portion goes into the ground vegetation, the soil microbial population, and, particularly in the case of P, becomes chemically fixed within the soil. The rate at which the nutrient will be then released from such pools is so slow as to be of negligible importance for subsequent tree growth. The only fraction that is important for tree growth, therefore, is that taken up by the trees soon after application and as this is used up growth declines until no further response is detected. This leads to the simple concept that fertilizers are applied to the trees, not the site. However, where the amount of nutrient applied is high relative to the active reserves within the soil, as can be the case with P or some trace elements, a long-term response may be recorded. Indeed in many areas around the world it is observed that although P had to be applied to the first rotation no further application may be needed in the second rotation.

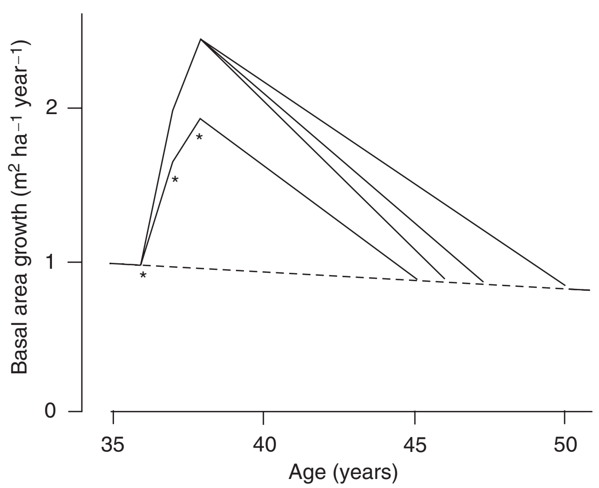

Figure 3 Basal area growth response shown by pine to nitrogen fertilizer applied at four rates in the 3 years marked with asterisks. Fertilizer treatments shown by solid lines and the untreated control by the dashed line.

When and How Much Fertilizer to Apply

In old coniferous forests of northern regions the immobilization of large amounts of N in the humus can lead to N deficiency and growth will respond to the application of fertilizer. For reasons of discounted cash flow such an application is usually made only 5–10 years before felling. More generally, however, fertilizer use is only necessary prior to canopy closure so a schedule such as that in **Table 6** might be appropriate.

The recommended rates of application vary remarkably little around the world and are generally, in terms of fertilizer element, are 150–200 kg N ha^{-1}, 60–80 kg P ha^{-1}, around 100 kg K ha^{-1}, and 7–10 kg ha^{-1} for both B and Cu.

Methods of Application

Often the most reliable method of application is still by hand to individual trees. An alternative while trees are still small is use of ground-based broadcast spreading equipment. However, as canopy starts to close both of these become impossible. Following crown closure aerial application, usually by helicopter, is the only option.

Environmental Considerations

Forest fertilization must be conducted so as to minimize negative environmental effects. The main concern is loss of nutrient into waterways where this might lead eutrophication, algal blooms and consequent damage to aquatic life, fisheries, and quality of drinking water. Applied fertilizer, therefore, must not fall into drains, streams, rivers, lakes, or reservoirs. This can seriously constrain the method of application chosen. The method often preferred is to apply by hand to individual trees. If other approaches are used, particularly involving aircraft,

Table 6 Suggested schedule for fertilizer application to spruce on different soil types (brackets indicate possible benefit)

Soil type	*At planting*	*Years after planting*			
		6	9	12	15
Brown earth	(P)	—	—	—	—
Iron podzol	P	—	P	—	—
Peaty podzol	P	—	P K	—	—
Heathland podzol	P	(N) P	N	N P	N

there has to be very careful planning and precise guidance (ideally using geographical positioning system (GPS)), accompanied by suitable supervision and monitoring, even although this may necessitate leaving significant areas untreated. Care must also be taken to ensure that that no leakage occurs from any storage stack in the woods and that all fertilizer bags are properly disposed of.

See also: **Health and Protection**: Biochemical and Physiological Aspects. **Soil Biology and Tree Growth**: Soil and its Relationship to Forest Productivity and Health. **Soil Development and Properties**: Nutrient Cycling. **Tree Physiology**: A Whole Tree Perspective; Mycorrhizae; Nutritional Physiology of Trees.

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Soil Contamination and Amelioration

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Introduction

Human activities have shaped and altered essentially all ecosystems on earth. Forest ecosystems are no exception to this and the effects of these activities can be observed throughout the forests of the world. While many of the activities leading to soil contamination have been necessary and positive (e.g., development of a sustainable agricultural system capable of feeding a growing world population), negative side effects are also widespread. Impacts range from clearly visible effects like unsustainable and large-scale logging and surface mining with all their associated problems of erosion, loss in soil fertility and productivity, and acid mine drainage, to less obvious effects including diffuse deposition of atmospheric pollutants or acid rain due to burning of fossil fuels. Many of these negative effects are reversible, and in particular, forested areas have the ability to buffer environmental impacts. Many physiological processes in forest systems such as evapotranspiration, photosynthesis, solute uptake, and effects of plant root exudates on contaminant degradation can be used to mitigate negative impacts and/or remediate existing contamination. This article focuses on forest soil contamination with regard to inorganic and organic contaminants and potential remedial strategies.

Soil Contamination

Contamination is generally grouped by origin as resulting from point (direct) or nonpoint (diffuse) sources. Point sources of soil contamination include spills and leaks, local emissions, and land applications, while atmospheric deposition and agricultural runoff are the main nonpoint sources of contamination. Point sources such as industrial outfall pipes or chemical spills are discrete, localized, and can be readily assessed and delineated, while nonpoint sources are more difficult to assess due to the large areas that can be affected and multiple sources that may contribute to the problem. Inorganic contaminants like trace metals and in some cases radionuclides (e.g., Chernobyl accident in 1986) can originate as both point sources and nonpoint sources. Organic contamination generally results from point sources, although elevated levels of some recalcitrant