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Birch Coppice Woodlands near the Sudbury Smelters: Dynamics of a Forest Monoculture

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The combination of environmental stresses to which the Sudbury region has been subjected has led to a series of distinct zones of vegetation surrounding the smelters. Closest to the smelters is a 170-km² zone of barren land that is nearly completely devoid of plant life. Adjoining the barrens is a 720-km² semibarren area, a zone of transition between the barrens and the natural plant community of the region (see Chapter 2). The two zones, the barren zone and transition zone (Amiro and Courtin 1981), are the direct result of human activity, and neither is found naturally as a successional stage of the eastern hemlock-white pine-northern hardwood forest (Braun 1950) that was once typical of the area.

The transition zone is divided into two largely monocultural communities, one dominated by white birch (*Betula papyrifera*) and the other by red maple (*Acer rubrum*), although each species may be found in the community dominated by the other (Amiro and Courtin 1981). The birch transition community is the more widespread of the two communities and occurs across a variety of slope and soil conditions, whereas the maple transition community is mainly restricted to glacio-fluvial deposits. Both communities are composed of trees with unique growth characteristics that become more prominent as one approaches the edge of the barrens. The multiple stems and slow growth of the trees in the birch transition forest is one of the more conspicuous

of these altered features. Such trees are described as "coppiced."

Coppicing is a term usually used to describe a form of biomass rejuvenation that has been a management practice in Europe for hundreds and sometimes even thousands of years (Buckley 1992). In the preface to his recent book, Buckley (1992) described the process as follows:

All coppice woodlands have one thing in common—they are repeatedly cut down, in the very reasonable expectation that the trees will regrow by themselves. Whether this regrowth is the result of new shoots sprouting from cut stumps or tree roots is unimportant: the point is that the new canopy forms rapidly and, for the main part, vegetatively from the old, without the need for any great management effort. The process is almost infinitely repeatable.

In North America, coppicing has rarely if ever been used as a forestry management practice; however, the birch transition forest of Sudbury does fulfil the above definition, except that the agency of biomass removal is not direct as would be the case with cutting, but rather, it is the indirect result of human impact. Nevertheless, the impact is cyclic, and the effects that result are both biotic and abiotic. In this chapter, I describe some of these processes by which this unique plant community is maintained in a stressed ecosystem.

FIGURE 18.1. (**A**) Aerial view from 10 m of a typical birch transition community to indicate the general morphology of the woodland and the absence of surface vegetation. (**B**) Example of a large birch coppice (stem diameter >5 cm at a height of 20 cm).

Site Characteristics

The birch transition forest (Amiro and Courtin 1981) is characterized by small aggregates of highly coppiced birch that are usually widely spaced such that the gaps in the canopy are often larger than the coppice aggregates themselves (Fig. 18.1). Relatively few other vascular and non-vascular species exist among the birch coppices (Table 18.1). Oke (1987) spoke of such strong vegetational contrasts as having a micro "oasis effect," and therefore, the present assemblage of coppices and the gaps between them, because of their relatively small size, is considered to form a mosaic of micro-oases and microdeserts. Each birch coppice rarely achieves a height of more than 6 m and a diameter of 12 cm, and few individual stems

exceed 30 years of age (James and Courtin 1985; Trépanier 1985). It is important to note that stools from which the individual coppices arise are considerably older than the maximum age of the coppices, as is the case in traditional European coppice woodlands. Attempts to age the Sudbury stools have proved impossible, owing to the chaotic ring pattern that results from the cyclic regrowth of the aerial portion (Courtin, *unpublished data*). Although no records exist other than photographs (see, for example, Wallace and Thomson 1993), I estimate that the forest in its present form probably arose during the time of open-bed roasting that occurred during the first quarter of the century (see Chapter 2).

Birch transition sites typically have very acid soils (pH < 4.2) that result in high ex-

TABLE 18.1. Importance Indices of the Major Species of Trees, Shrubs, Herbs, and Bryoids Found in the Birch Transition Forest[a]

	Mean importance index	Standard error
Trees		
Acer rubrum	1.5	(0.6)
Betula papyrifera	27.7	(1.9)
Populus tremuloides	4.4	(1.4)
Shrubs		
Acer rubrum	5.2	(1.5)
Betula papyrifera	21.8	(3.4)
Populus tremuloides	4.2	(1.6)
Salix bebbiana	6.2	(1.4)
Salix discolor	0.9	(0.6)
Herbs		
Agrostis scabra	13.3	(2.4)
Betula papyrifera	9.8	(3.1)
Calamagrostis canadensis	5.9	(1.7)
Comptonia peregrina	6.7	(2.6)
Cornus canadensis	3.7	(1.6)
Deschampsia flexuosa	12.5	(3.8)
Diervilla lonicera	4.3	(2.2)
Vaccinium angustifolium	23.9	(4.9)
Bryophytes and lichens		
Pohlia nutans	37.8	(4.5)
Polytrichum commune	5.9	(1.6)
Stereocaulon spp.	5.0[b]	
Other		
Bare rock	29.0	(4.6)
Bare soil	28.6	(4.3)
Dead material	67.5	(3.0)

[a]From Amiro 1979. The importance index is based on the density, frequency, and cover of a given species relative to all other species in a given layer.
[b]Estimated.

tractable levels of copper, nickel, aluminum, and manganese (James 1982). Sudbury's transition and barren zone soils are prone to heave, owing to segregated ice and needle ice formation. The reason is that the so-called heavable fraction, the silt and very fine sand textural classes, compose approximately 50% of the mineral material in the upper 50 cm of the soil column. The remainder is made up of coarse and fine sand (approximately 35%) and the balance is clay (Sahi 1983). Schramm (1958) stated that soils are susceptible to heaving when they con-

tain substantial amounts (about 30%) of particles smaller than, and including, the very fine sands (i.e., < 70 µm in diameter).

Effects of Microclimate

The microclimate within the birch transition forest is governed almost entirely by the structure of the stand (Fig. 18.2). In summer, the canopy openings are areas where solar irradiance penetrates to the soil surface during the day, which results in high soil surface and tree canopy temperatures (Table 18.2), whereas the micro-oases are cooler by virtue of surface shading, evaporative cooling from the soil, and transpiration. The soil surface with its temperatures as high as 70°C provide an environment that causes most of the birch seedlings recruited the same spring to die by desiccation. In autumn, it is the nighttime reradiation regime that strongly influences the micro-deserts. On clear calm nights, any solar radiation stored as heat during the day is rapidly lost to the night sky, with the result that freezing of the surface soil layers gives rise to the formation of either segregated ice lenses or needle ice (Fig. 18.3). This vertical displacement of the soil by ice uproots the majority of seedlings that either managed to survive the summer drought and heat or were recruited to the site in early autumn, a period characterized by frequent rains. It is also the presence of wet or even saturated soils that provides the moisture source for the frost effects observed in autumn. The processes just described are summarized schematically in Figure 18.4.

Just as there is a mosaic pattern to the entire woodland, so too is there a mosaic pattern within the microdeserts. The ice formation and heaving of the soil occurs in very localized areas. At the edge of these areas of extreme surface instability (Fig. 18.5A), the occasional white birch seedling manages to survive past the first, critical growing season but grows extremely slowly for several years because of soil drought in summer and severe pruning of the roots through frost action in the autumn. These trees can be referred to as "bonsai" birch
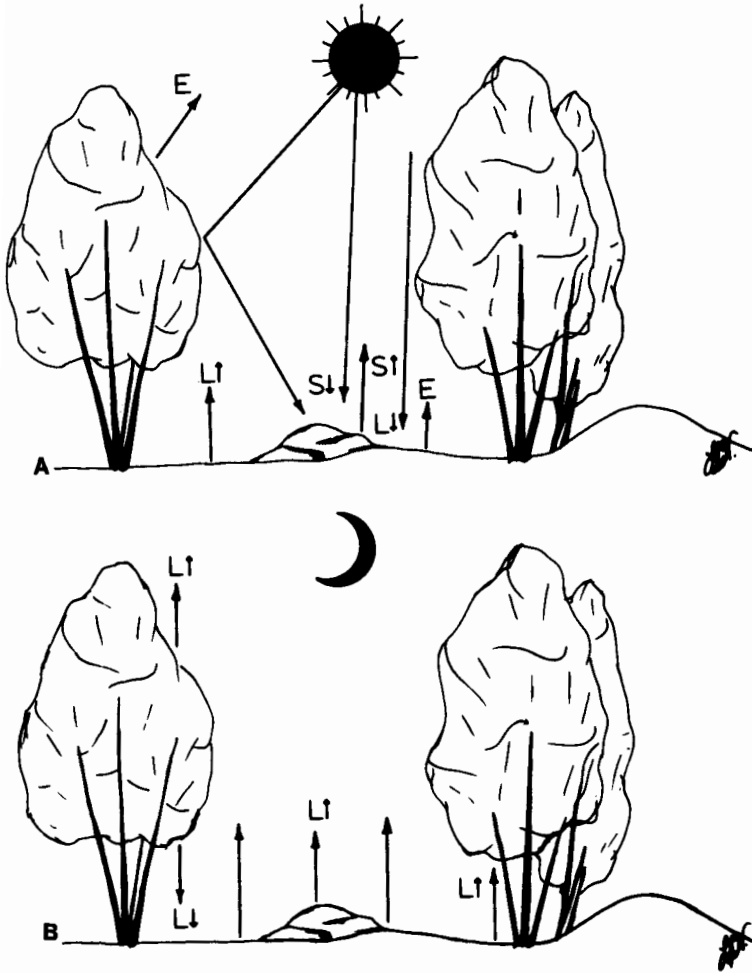
FIGURE 18.2. Schematic representation of the major shortwave (*S*), longwave (*L*), and evapotranspiration (*E*) fluxes operating in the birch coppice woodland during the day (**A**) and during the night (**B**).

(Fig. 18.5B). Their stunted growth mimics, in part, the Japanese horticultural practice for producing dwarf trees.

Effects of Insects

The dominance of white birch across much of the Sudbury landscape has led to an insect problem analogous to that found in agriculture. A monoculture provides an abundance of the same food source, and insect outbreaks rapidly reach epidemic proportions. The chronic stress due to contaminated soils that plants are subjected to in industrial areas may also increase the trees' susceptibility to insect attack (Louda 1988; Riemer and Whittaker 1989). Also, the ability of pathogens or other natural

TABLE 18.2. Typical Values of White Birch Physiological Response and Environmental Conditions on Days with Fine Weather between June 11 and July 31, 1981*

| Parameter	Range of values
Temperature (°C)	
Air	21–26
Leaf	27–28
Soil surface	40–70
Stomatal conductance (s/m)	12–125
Shoot water potential (MPa)	−1.25 – −1.3
Gravimetric water content (g/gDW)	
0–5 cm	0.12–0.40
10–15 cm	1.12–0.40

*From James 1982; Courtin, *unpublished data.*

FIGURE 18.3. Examples of frost disturbance within the birch coppice woodland owing to heaving of the entire surface soil through the formation of segregated ice lenses (**A**) and efflorescence of needle ice covering an area of about 2 m² (**B**). Ice lenses typically displace the soil vertically up to 3 cm, whereas needle ice often exceeds 10 cm in height.
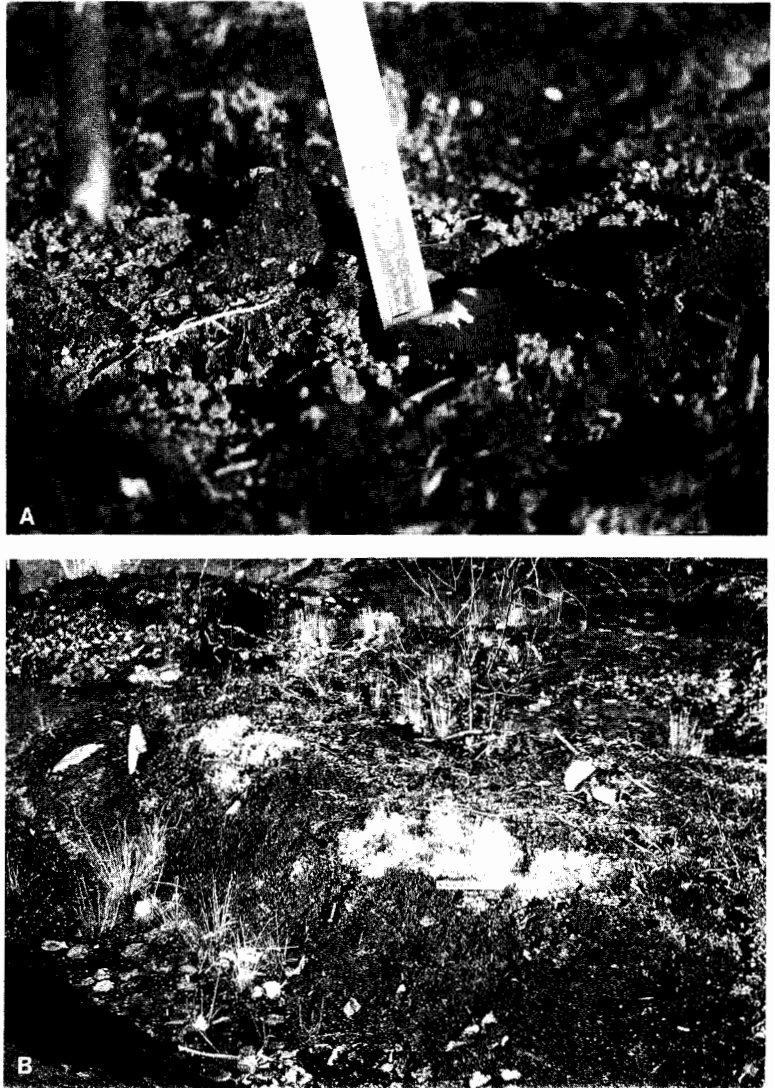
enemies to control herbivorous insects may be reduced at industrially affected sites (Haukioja 1992).

Several insects representing different orders and each having a cycle of abundance that is different from the others have subjected birch in the Sudbury area to an almost unremitting onslaught of either damage or defoliation (Fig. 18.6). The leaf miners (*Messa nana, Fenusa pusilla*) were numerous in the late 1970s through 1975, but their impact on the Sudbury birch is unknown. In 1986, a single severe infestation of birch sawfly (*Arge pecto-*

ralis) completely defoliated many trees. At least some of these trees have died subsequently, indicating that the loss of leaves (even though late in the season after the majority of photosynthetic storage for the following spring was completed) caused a shock which they were unable to overcome. At least three major infestations of forest tent caterpillar (*Malacasoma distria*) have occurred over the past two decades. The primary target has been trembling aspen (*Populus tremuloides*), but the insect tended to move to birch once the aspen food source was exhausted. Each infestation has
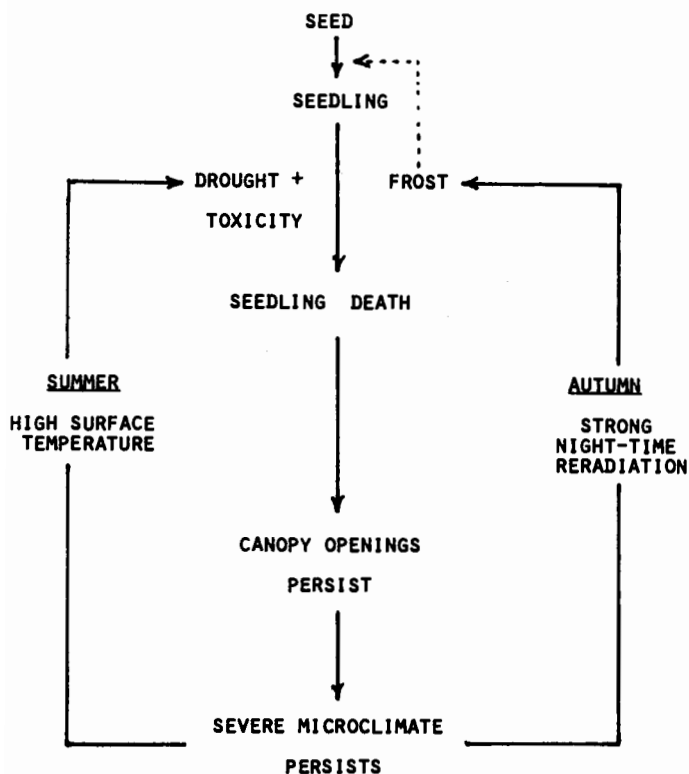
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          │              ▼                                 │
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          │              │                                 │
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          └──── SEVERE MICROCLIMATE ────────────────────────┘
                   PERSISTS
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FIGURE 18.4. Model of the barriers to seedling establishment in the birch coppice woodland.

lasted 2–3 years, until checked by natural predators.

The most serious problems have been caused by bronze birch borer (*Agrilus anxius*). Its method of attacking the cambium layer beneath the bark causes girdling and subsequent death of the stem. In the spring after the first attack, the emerging canopy is comprised of very small leaves, and there is an abundance of female catkins. This proliferation of reproductive tissue in birch after insect attack is perhaps analogous to the production of "agony cones" in stressed conifer species.

Three years ago, the gypsy moth (*Lymantria dispar*) reached Sudbury from eastern Ontario, and although the heaviest damage has been on red oak (*Quercus borealis*), the larvae also vigorously attack trembling aspen and white birch. A generalization that can be made with respect to all the above insects is that attack is always more severe at the edges of stands than within stands. The reason is presumed to be the ease of accessibility on the one hand and a warmer microclimate on the other. In the coppice woodland, with its large canopy openings, most trees are therefore vulnerable to insect attack.

Comparison with Other Simplified Ecosystems: High Arctic Tundra

One result of the combination of anthropogenic stressors that exist in the Sudbury area is the simplification of the entire food web. The dominant trophic level is the primary producer but with low species diversity. The spatial distribution of the vegetation leads to a very harsh microclimate that has a tremendous impact on the remainder of the food web. The dominant herbivores are the insects and the dominant carnivores are the insects that feed on the herbivorous insects. The cop-

FIGURE 18.5. Examples of effects of frost disturbance in the birch coppice woodland. (A) Frost hummock showing patches of bare soil, patches of fragmented moss, and tree roots that have been heaved to the soil surface. (B) A *Bonsai* birch "seedling" that is 7 years old but only 15 cm high. Note the distorted trunk (just above the thumb) owing to repeated heaving, the very shallow root system with few feeder roots, and the branching just above the root collar that is an indication that coppicing has already begun.

pice woodland with its large canopy openings offers little shelter for vertebrates so that the only representatives are a few insect-eating birds in summer and a few seed-eating birds in winter. No sign has been found of either voles or mice, and the occasional larger mammals such as red fox (*Vulpes vulpes*) and red squirrel (*Tamiasciurus hudsonicus*) uses such sites simply as a travel route. Again, because of microclimate extremes, the litter accumulates only in sheltered depressions, and decomposition is very slow because of drought and heat in summer and surface reradiative cooling in spring and autumn. In essence, the ecosystem simplicity that one observes near Sudbury not only rivals that of the High Arctic tundra but possibly exceeds it (Table 18.3).

Although the driving forces are different in most cases, the results are very similar. Chamaephytes dominate in the arctic and phanaerophytes dominate in Sudbury, but both are dwarfed. Reproductive success through seeds
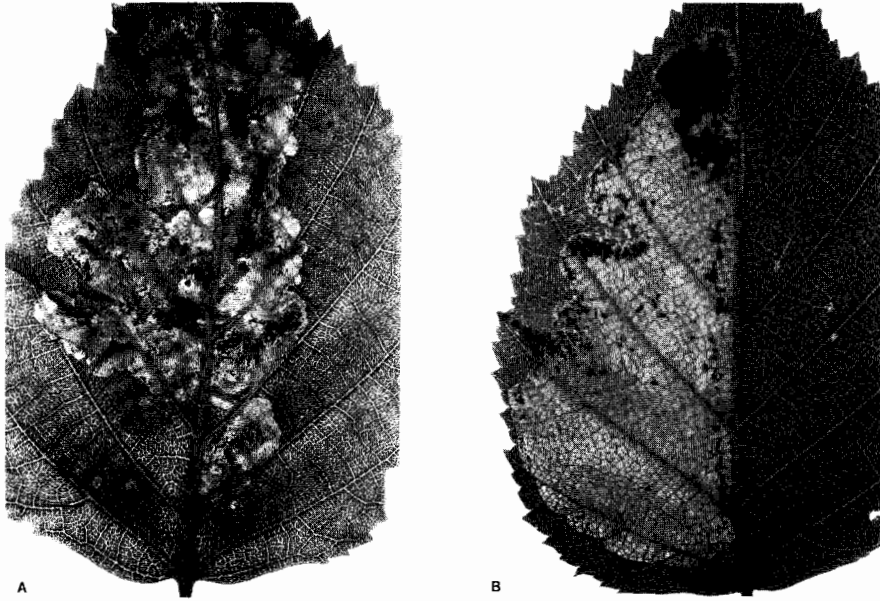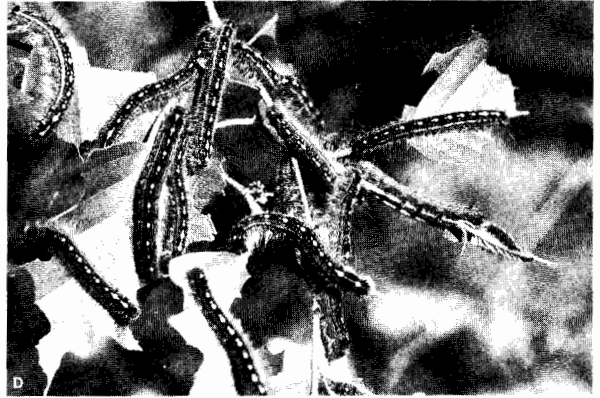
FIGURE 18.6. Insects that attack white birch in Sudbury area. (**A**) leaf miner (*Fenusa pusilla*) larvae within birch leaf; (**B**) leaf miner (*Messa nana*) larvae within birch leaf; (**C**) birch sawfly (*Arge pectoralis*) larvae; (**D**) forest tent caterpillar (*Malacasoma distria*) larvae; (**E**) gypsy moth (*Lymantria dispar*) larvae; (**F**) bronze birch borer (*Agrilus anxius*) adult. (Photos by J.D. Shorthouse.)

in both systems is low. Decomposition is slow, in the arctic because of cold and in Sudbury because of drought, metal toxicity, and low pH. Even the dominant characteristic of patterned ground through frost action in the arctic (Washburn 1956) is found in a modified form in Sudbury.

Discussion

Long-term changes in the birch transition forest toward greater environmental stability and species diversity is predicated on two possible mechanisms operating either separately or in concert. Amelioration of the severe surface
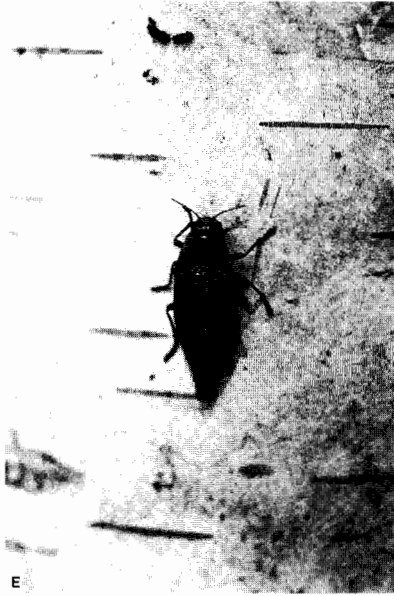
FIGURE 18.6. (*Continued*).

microclimatic conditions could take place if the ground vegetation of herbs, shrubs, tree seedlings, and mosses develops sufficiently to provide (1) a closed canopy to reduce intense surface radiation and reradiation, (2) a litter layer that does not become redistributed by wind, and (3) a network of roots that bind the soil. Alternatively, the same ends would be achieved either by complete closure of the tree canopy or a combination of both increased tree cover and ground vegetation cover (Fig. 18.7). With the progressive curbing of air pollution in recent years, the way seemed to be paved for major improvements in health, vigor, and diversity of Sudbury's vegetation. In fact, in the early 1970s, birch did appear to be growing better than in the past. At that time, however, there were no quantitative data on

Table 18.3. Characteristics of Industrially Disturbed Sudbury and High Arctic Tundra Ecosystems

Characteristic	Industrially disturbed	Tundra[a]
Temperature extremes	Microclimatic owing to site characteristics	Macroclimatic owing to latitude
Low species diversity	Historical	Climatic
Low productivity	Acid, metal-toxic soils	Climatic
Slow decomposition	High surface temperatures and drought	Low summer temperatures; short snow-free season
Low fertility	Low cation exchange capacity owing to low pH	Slow decomposition owing to cold and anaerobic conditions
Drought	Physically induced owing to topography	Physiologically induced owing to frost action and anaerobic soils
Frost disturbance	Diel freeze-thaw owing to clear sky reradiation; formation of needle ice and ice lenses	Seasonal freeze-thaw owing to macroclimate; formation of patterned ground

[a]Studies from Devon Island (Bliss 1977; Courtin and Labine 1977) are used to provide the overviews for the tundra.
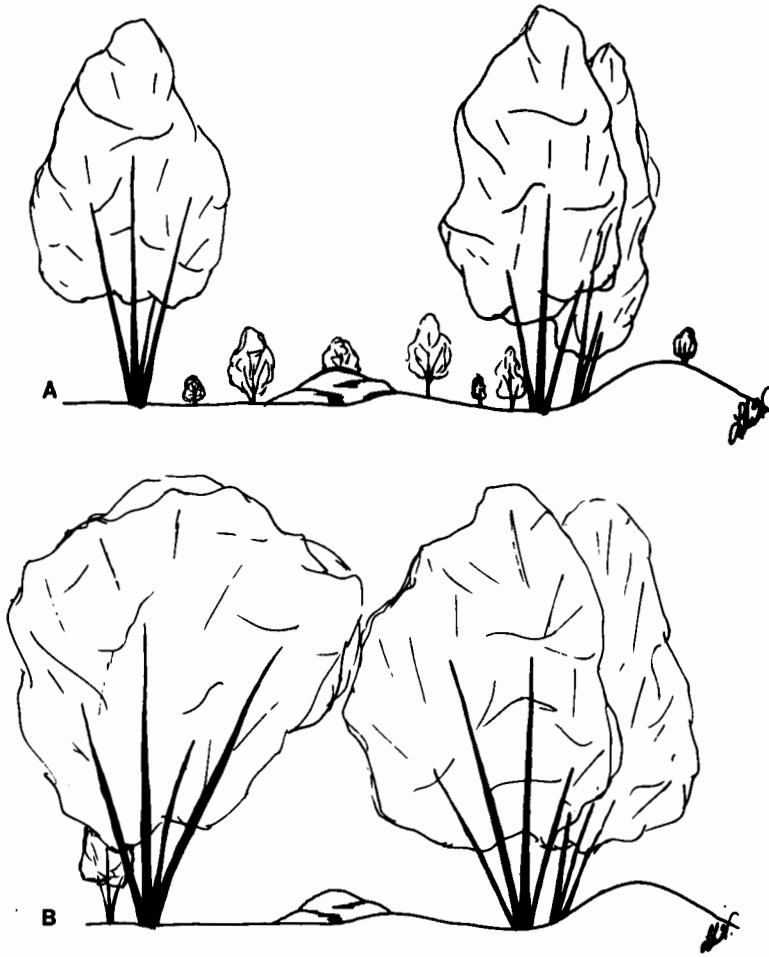
FIGURE 18.7. Schematic representation of the two possible strategies proposed for long-term site stability and increase in diversity through microclimatic amelioration. (**A**) Establishment of seedlings and other growth of low stature; (**B**) canopy closure of the existing coppices.

productivity, and it appears that if there was an improvement, it was short-lived. My observations of the birch coppice woodland over a period of 25 years and research into its dynamics since 1977 indicate that little if any unidirectional change toward a stable and more diverse community has taken place (Fig. 18.8).

The most plausible explanation for the long-term lack of change may be found in the nature of the coppice birch woodland itself, first because of its structure and second because it is a monoculture. Drought and frost, combined with acid, metal-toxic soils, operate to minimize the recruitment of birches from seed and totally eliminate all seedlings of red maple, the other dominant tree species. Hence the first mechanism proposed for microclimatic amelio-

ration (i.e., the revegetation of canopy openings) is unlikely to occur rapidly. However, there has been an increase in recent years in the cover of the acid-loving mosses *Pohlia nutans* and *P. cruda*, and Sahi (1983) observed that the most frost-stable areas were those that were moss-covered. Cracks develop in the moss through desiccation, and birch seeds lodge in these cracks and germinate. The mulching effect of the moss seems to provide a moist and stable seed bed that, in time, may increase the numbers of birch that establish from seed.

The second mechanism, that of canopy closure of the existing coppices, is unlikely to occur, because in such a monoculture, the forest appears particularly prone to the cyclic and often devastating effect of defoliating insects. Entire coppices have been observed to die

FIGURE 18.8. Birch transition coppice woodland. (**A**) Photograph taken in 1980; (**B**) photograph taken in 1993. Few changes have taken place in the intervening years.

after complete defoliation by birch sawfly in late summer, and bronze birch borer kills any stem that it attacks because its larvae totally girdle the tree in 2 years. In recent years, bronze birch borer has increased in numbers to the point where as many as 90% of stems in some stands have been killed. However, attack by insects stimulates growth of basal sprouts to re-initiate the coppice cycle in the same way that cutting does in conventional coppice woodlands.

Without the intervention of soil amelioration (liming and fertilizing) and the re-introduction of native conifers (white and red pine, white spruce) it is unlikely that any rapid uni-directional change will take place in the upland birch woodlands. The planting of the adjacent barrenlands to conifers (see Chapter 8) will provide a future seed source, but seedlings will probably suffer the same fate as deciduous seedlings that attempt to become established. With soil amelioration, however, changes could be much more rapid. Winterhalder (1983) reported that planting trials on the barrens that received lime demonstrated better growth than unlimed trial plots. He suggested that survival in summer was drought-dependent, whereas winter survival was a function of the degree of frost-heaving. Liming alone, therefore, might well reduce the degree of

frost damage sufficiently and increase the rate of seedling growth to the point at which revegetation of canopy opening is great enough to reduce significantly the extremes of surface microclimate. There certainly is evidence that liming improves growing conditions, but it is unlikely that improved growth will necessarily mean greater plant diversity unless other tree species, especially conifers, are planted, as has been the case for the reclaimed barrens (see Chapter 8). According to Winterhalder (*personal communication*), the liming of organic soils stimulated the growth of 10 species that had been lying dormant as part of the seed bank. Winterhalder (1983) found that the birch transition seed bank only contained white birch and tickle grass (*Agrostis scabra*). The paucity of a natural seed source is a further indication that recovery of the birch ecosystem, without human intervention, will probably be extremely slow.

The observed effects of smelter emissions on vegetation are not unique to Sudbury. Other climatically similar areas such as northern Russia, where birch is also a dominant species, have suffered serious damage from nickel and copper smelting (Kryuchkov 1993). It is hoped that the work on barriers to vegetation recovery performed in Sudbury may aid other workers attempting restoration of mine-damaged lands elsewhere.

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