ECOSYSTEM RECOVERY AFTER EMISSION REDUCTIONS: SUDBURY, CANADA

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Abstract. A case history is presented describing the ecosystem changes that accompanied the nearly 90% reduction of SO_2 and metal particulate emissions from Sudbury smelters during the past 25 years. The instances of severe ground-level fumigations that caused acute damage to vegetation in an area of approximately 1,000 km^2 have been nearly completely eliminated. Significant improvements in water quality have also occurred in many of the estimated 7,000 acid-damaged lakes. Several species of acid-sensitive phytoplankton, zooplankton and insects have invaded lakes where improvements have occurred. Epiphytic lichens have reinvaded the former "lichen desert" that once extended out 7 km from the smelters. Sensitive species such as Evernia mesomorpha and Usnea hirta now exist throughout the area. The vascular plant communities have been relatively slow to recover in the most severely damaged terrestrial areas. Metal-tolerant grasses (e.g. Agrostis scabra, Deschampsia caespitosa) were the first species to invade the barrens. Acid- and metal-contamination of soil, severe microclimate conditions, and the damaging effects of insect pests appear to delay recovery of terrestrial ecosystems. Recovery rates of aquatic ecosystems are also affected by a suite of physical, chemical and biotic interactions and many lakes remain severely damaged.

Key words : recovery, smelter, acidification, copper, nickel

1. Introduction

During the past century of mining and smelting in the Sudbury area more than 100 million tonnes of SO_2 and tens of thousands of tonnes of Cu, Ni and Fe have been released into the atmosphere from the open roast beds (1888-1929) and smelters (1888-present). Rivalled in magnitude only by the metal smelting complex in Noril'sk Russia, Sudbury at its peak (1960 - 2.56 million tonnes of SO_2), contributed approximately 4% of the global sulphur emissions (Freedman, 1989). The vast environmental damages resulting from the Sudbury emissions include approximately 20,000 ha of nearly completely barren land, approximately 80,000 ha of semi-barren area, and an estimated 7,000 acid-damaged lakes (Figure 1). Severe contamination of surface soils, water and lake sediments by atmospherically deposited metals also occurred at sites within approximately 30 km from the smelters (Whitby *et al.*, 1976; Nriagu and Roa, 1987; Keller *et al.*, 1992a; Dudka *et al.*, 1995.)

In the past 25 years, production of Ni (Figure 2a), Cu and other metals has been maintained at high levels while industrial SO_2 emissions have been reduced by approximately 90% (Figure 2b) through a combination of industrial technological developments and legislated controls. This paper reviews the evidence of improved air quality and natural recovery (i.e without liming or other remedial measures) of damaged aquatic and terrestrial ecosystems during this period of reduced emissions at Sudbury. See individual papers in Gunn (1995) and other cited references for details.

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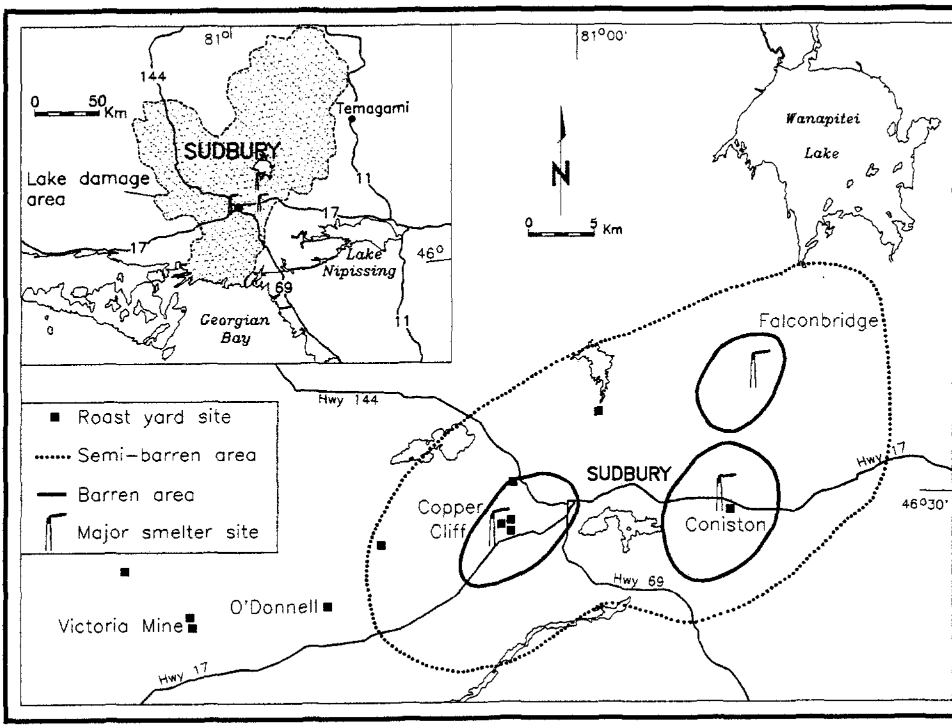

Figure 1. Location of the major sites of roasting and smelting activity in the Sudbury area. The areas of vegetation damage are based on 1970 aerial photography (McCall et al., 1995). The larger area of lake damage, assessed by extensive water quality surveys (from Neary *et al.* 1990), is illustrated in the insert (maps by L. Lariviere).

2. Changes Following Emission Reductions

2.1 AIR QUALITY AND ACUTE VEGETATION DAMAGE

The combination of plant closures, major reductions in emissions, greater dispersal through tall stacks (e.g 381 m stack constructed by Inco Ltd in 1972), and a ground level monitoring program that regulates daily industrial operations, has been successful at greatly reducing both the annual SO_2 concentration (below the 0.02 ppm government criteria) (Figure 2c) and the instances of short-term ground level fumigations that cause acute damage to vegetation (Potvin and Negusanti, 1995). There are still areas within about 10 km of the smelters where ground-level concentrations of SO_2 occasionally exceed the established hourly limit of 0.5 ppm, but the number of potentially damaging daytime fumigation events (criteria: $SO_2 \geq$ 0.95 ppm for 1 hr; $\geq$ 0.55 ppm for 2 hr; $\geq$ 0.35 ppm for 4 hr; or $\geq$ 0.25 ppm for 8 hr) has been greatly reduced (Figure 2d). Even areas near the smelters can now be replanted with tree species such as the white pine (Pinus strobus), which is among the most sensitive species to SO_2 injury. Emissions controls have done little to reduce the acidity or metal contamination of soils in the barren area (Hutchinson and Whitby, 1974; Dudka *et al.*, 1995), and the large-scale reestablishment of conifer tree species is mainly dependent on liming and other soil amelioration procedures (Lautenbach *et al.*, 1995).

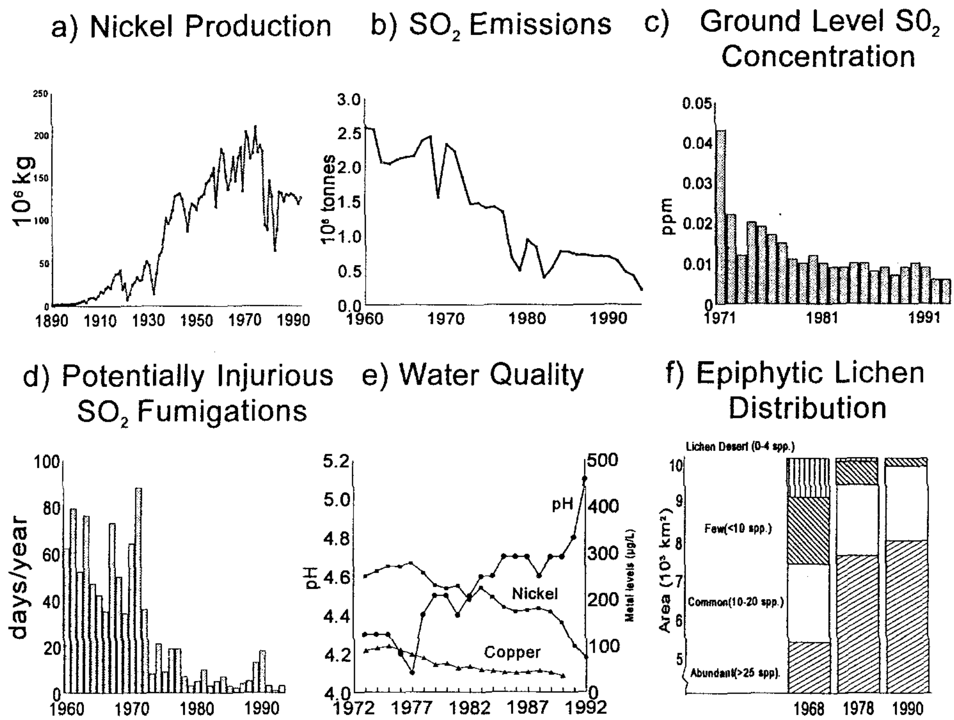

Figure 2. Annual Ni production (a) and SO_2 emissions (b) from the Sudbury area. Annual average air-borne SO_2 concentration at three ground-level monitoring stations (Garson, Skead, Ash Street) within the vegetation damage zone (see Figure 1) (c). Frequency, during the growing season (mid-May to mid-Oct), of ground-level SO_2 fumigations that are potentially injurious to vegetation (d). Changes in lake water pH and dissolved metals in Clearwater Lake a 75 ha lake located 11 km from the Copper Cliff smelter (OMOEE unpubl. data) (e). Changes in the occurrence of epiphytic lichens within a 10,000 km^2 area surrounding the three smelter sites. Number of species of lichens in each category indicated (f).(Graphics by M. Conlon and R. Sein).

2.2 WATER QUALITY AND AQUATIC COMMUNITIES

As emissions of SO_2 declined, sampled lakes exhibited an increase in pH (Figure 2e) and alkalinity and a decline in sulphate and metal contamination (Figure 2e). Reduced acidic deposition has also reduced the mineral leaching of watershed soils, resulting in reductions in the lake water concentrations of base cations (Ca and Mg) and readily leachable metals (Al and Mn) (Keller *et al.*, 1992a). Although water remains acidic and heavily contaminated with metals in large numbers of lakes, the observed improvements to date have allowed a variety of organisms to recolonize individual lakes. Fossil records in the sediments provide clear evidence of the rapid recovery of planktonic diatoms and chrysophytes (Dixit *et al.*, 1989). Increasing species richness of crustacean zooplankton, phytoplankton, and benthic invertebrates have all been observed (Gunn and Keller, 1990; Keller *et al.*, 1992b). However, species with limited dispersal ability such as fish, decapods, mollusks and amphipods, are slow to colonize and will probably require assistance from large-scale reintroduction programs by management agencies to ensure their rapid return.

2.3 EPIPHYTIC LICHENS

Epiphytic lichens, plants that are particularly sensitive to air pollution, have responded rapidly to improving air quality in the Sudbury area. Surveys of epiphytic lichens growing on mature balsam poplar (Populus balsamifera) trees were conducted in 1968 (pre emission reduction period), 1978 and 1989-90 (Beckett, 1995). More than twice as many species were recorded near the smelters in the 1989-90 study as were observed in 1968. In 1968, no lichen species occurred within a radius of seven kilometres from the three smelters (Leblanc *et al.*, 1972). Between seven and fifteen kilometres only the crustose lichens Bacidia chlorococca, Lepraria aeruginosa, Lecanora saligna and the foliose lichen Parmelia sulcata were present. By 1990, no sampled trees were found to be devoid of lichen epiphytes, and the more SO_2 tolerant species (listed above) were found within two kilometres (the minimum sampling distance) of the two existing smelters (Figure 2f). Some pollution-sensitive species reinvaded the area much faster than expected, and recolonization did not follow an orderly sequence with pollution-tolerant species invading ahead of sensitive species. Results from the 1990 survey indicated that fruticose species, previously reported as rare and SO_2 sensitive (Usnea hirta and Evernia mesomorpha), occurred much closer to the smelter (5 km) than expected (Beckett, 1995). Although epiphytic lichens have shown recovery in the past 20 years, lichens on rocky outcrops (saxicolous) and on soil (terricolous) appear to be much slower to respond. Continuing high acidity and metal contamination of soils may be responsible for slower ground colonization rates since limestone-treated areas support a diverse lichen flora 15 years after treatment (Beckett, 1995).

2.4 VASCULAR PLANTS

Recovery of vascular plants in the barren zone has been very slow. Previous photo interpretive studies have shown that the recovery of the landscape near former roast beds (Figure 3a&b) proceeded through to the establishment of a relatively dense mixed forest cover during a 50 year period (Struik, 1974). In the barrens near the operating (Figure 1; Copper Cliff, Falconbridge) or abandoned (Coniston; closed in 1972) smelters, natural recolonization has been limited by the severe loss of soil through erosion and the extensive contamination of the remaining soil by toxic metals. Recolonization of the smelter barrens has therefore been mainly confined to moist, sheltered, nutrient-enriched sites, such as stream channels (Figure 4c&d), where sedges (Scirpus cyperinus, Carex retrorsa, C. scoparia) and willows (Salix pyrifolia, S. humilis, S. gracilis, S. lucida) quickly established themselves (Winterhalder, 1995). In more exposed barren areas, recolonization did not begin until at least ten years after the initiation of atmospheric improvement. Here the first colonizing species were metal tolerant strains of native grasses, particularly tickle grass (Agrostis scabra) and tufted hairgrass (Deschampsia caespitosa). Nón-native grasses (Agrostis gigantea, Poa compressa), again populations that exhibit genetically enhanced metal tolerance (Hogan *et al.*, 1977; Rauser and Winterhalder, 1985), have also colonized some of the barren sites, as have dwarf birch (Betula pumila) and the sheep sorrel (Rumex acetosella). In the case of woody plants that remained as relicts on the barrens, all species except red maple (Acer rubrum) either maintained or increased their size and vigour in the twenty years following 1970, whereas the red maple continued to undergo "regressive dieback". The white birch (Betula papyrifera), the most common tree species in the damaged area (Amiro and Courtin, 1981), exists both as a relict species and a new colonist, but continues to exhibit stunted growth (Figure 3e&f), presumably in response to the combined stress of toxic soils, severe microclimate conditions in the barrens (high surface temperatures, drought, ice heaving) and frequent insect infestations (includes: Agrilus anxius, Croesus latitarus, Messa nana, Malacascoma distria) (Courtin, 1994).

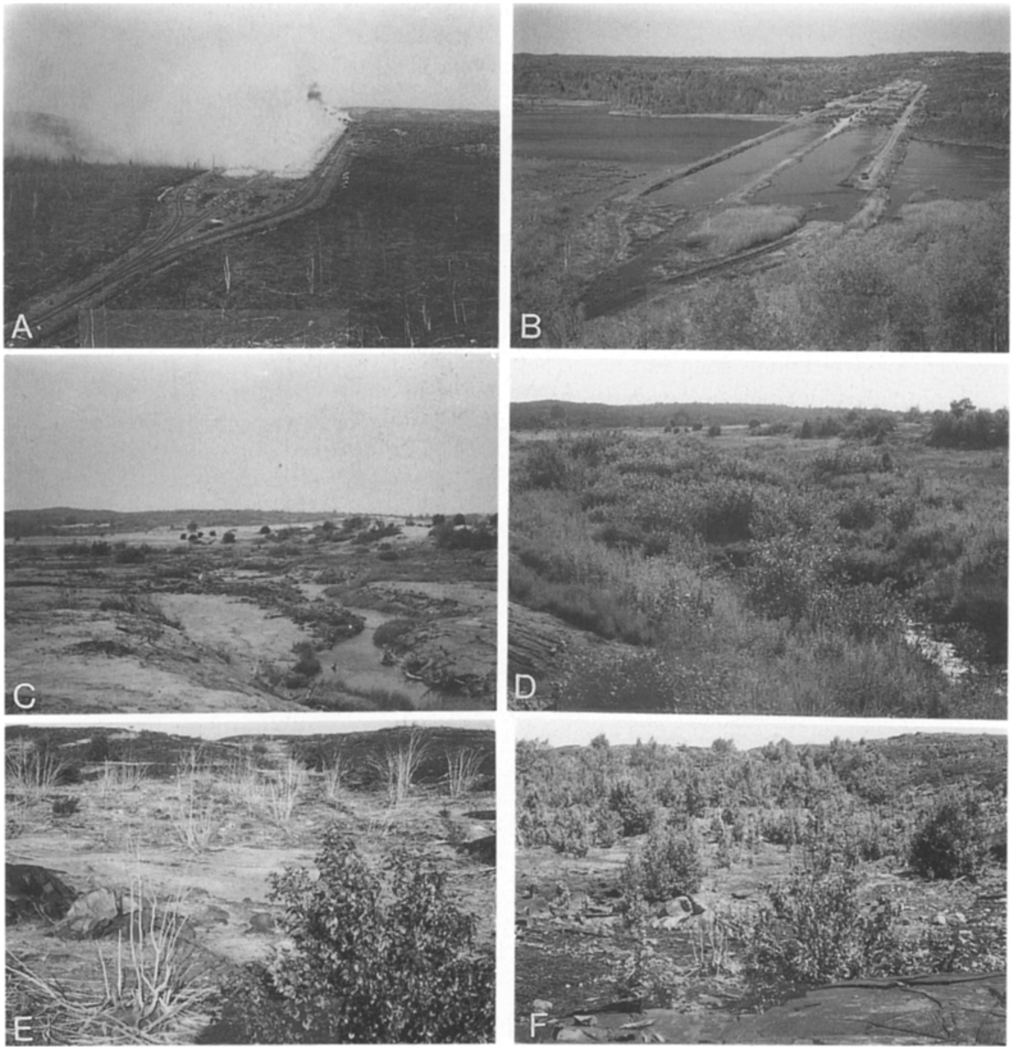

Figure 3. O'Donnell roast yard during operations in 1920 (a) and again in 1994 (b), 65 years after operations ceased. Valley of Coniston Creek, 4 km north of the Coniston smelter, in 1972 (c) and again in August 1984 (d). Site 3.5 km northwest of Coniston smelter in July 1980 showing relict white birch and numerous dead red maple (e) and again in June 1989 showing colonization by birch seedlings (f). (photos: a, Inco Archives; b, E. Snucins; c-f, K. Winterhalder).

3. Conclusion

The Sudbury case history provides strong support for emission control programs. Air and water quality and certain terrestrial and aquatic biota, particularly those with good colonizing ability and/or genetically evolved tolerances, have responded rapidly to the pollution abatement efforts at Sudbury. The observed resilience of natural systems is encouraging; however, further emission reductions and continued large-scale rehabilitation efforts will probably be needed to increase the extent and rate of recovery. Currently, the Sudbury smelters, at the combined legislated limit of 365,000 tonne of SO_2/yr, are still among the world's largest point sources of atmospheric emissions. Terrestrial soils remain very acidic and heavily contaminated with toxic metals, necessitating extensive use of soil liming as part of the Sudbury land reclamation program. To date (Sept. 1995) the municipal and industrial (Inco Ltd., Falconbridge Ltd.) programs have revegetated more than 4,000 ha of some of the most barren areas, including the planting of more than 3 million trees. Many aquatic systems, particularly those near the smelters, also remain heavily contaminated with metals, which may delay recovery. At remote areas within the Sudbury damage zone, metal levels are low, but few lakes have yet recovered above the suggested chemical threshold of pH 6.0 needed for protection of aquatic life. These lakes are also still impacted by long-range transport of acidic deposition from sources far from Sudbury. Liming is not considered feasible for these remote lakes, but restocking with fish and other sensitive organisms is planned once monitoring programs detect sufficient natural improvement.

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