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An examination of the micro-distribution of _Salsola pestifer_ Nels. in relation to a number of environmental conditions on the tailings of an iron mine as a preliminary to revegetation

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This thesis is submitted to the School of
Graduate Studies and Research in partial
fulfilment of the requirements for the Master
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D.C. Moore
September, 1980.

Abstract.

The problem of establishing a dense vegetative cover on an unamended section of the iron tailings of Hilton Mine, Bristol-les-Mines, P.Q. is examined. As illustrated by the literature, the revegetation of mine wastes is desirable so as to moderate the associated environmental degradation. Natural colonization has commenced at the study site. A single species, *Salsola pestifer* Nels. predominates, with only occasional, isolated individuals of other species present. However, there exist, as well, bare patches, both large-scale (minimum 25 m^2 in area) and small (generally less than 1 m^2 and located within vegetated zones). It is suggested that the establishment of a dense vegetative cover can be most readily realized through the expansion of the local *S. pestifer* population.

The data obtained *in situ* and in the laboratory support the conclusion that the large-scale bare areas possess properties antagonistic to *S. pestifer* ecesis, while the small-scale bare areas are amenable to the species ecesis but have not received its seed. Among the parameters examined, those found to be detrimental include: i) seasonal inundation, ii) substrate compaction prior to emergence and/or without compensating microrelief and iii) insufficient available N, P and K. The operation of additional limiting factors is also suggested.

Résumé.

Le problème de l'établissement d'une végétation sur une section non-amendée des déblais de la mine de fer Hilton, Bristol-les-Mines, P.Q., est examiné. Comme la littérature le montre, la revégétation des déblais est souhaitable de manière à modérer la dégradation de l'environnement. La colonisation végétale naturelle a déjà commencé sur le terrain. Salsola pestifer Nels. est la seule espèce dominante, accompagnée de quelques représentants isolés d'autres espèces. Il existe également plusieurs parties dépourvues de végétation, tantôt de grande étendue (plus de 25 m^2 de superficie) tantôt de petite étendue (généralement moins de 1 m^2 et comprises à l'intérieur de zones couvertes par S. pestifer). On suppose au départ que l'établissement de la végétation serait plus facilement accompli par l'expansion de la population locale de S. pestifer.

Les données obtenues sur le terrain et au laboratoire soutiennent la conclusion que les sections dénudées de grande étendue possèdent des propriétés défavorables à l'ecesis de S. pestifer. Par contre, les sections dénudées de petite étendue sont favorables à l'ecesis de l'espèce, mais elles n'ont pas reçu ses semences. Parmi les facteurs examinés, certains furent identifiés comme étant nuisibles à S. pestifer: i) l'inondation saisonnière, ii) le tassement du terrain avant que les jeunes plants n'émergent et/ou sans microtopographie avantageuse et iii) une insuffisance de N, P et K disponibles. L'action de facteurs limitants additionnels est aussi suggerée.

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1. Introduction.

1.1. Context of the Study.

Environmental degradation seems an inevitable attendant of man's activities. It is towards the rehabilitation of one such case - the wastes of an iron mine at Bristol-les-Mines in southwestern Québec - that this thesis is directed.

Surface mining, whereby a mineral or fuel deposit is excavated upon the removal of the overlying vegetation, soil and rock strata, produces considerable waste. This consists of i) overburden, the heterogeneous, unconsolidated organic and mineral matter removed to expose the bedrock or orebody, ii) waste rock, the non-ore or poor ore solid rock that is fractured and extracted and iii) tailings, the rejected products of the physical and chemical ore-separation processes.

Surface mine wastes covered approximately 45,000 ha (overburden: 21,000, waste rock: 7,000 and tailings 17,000 ha) of the Canadian landscape in 1977, according to data compiled by Murray (1977b). As mining activity continues, wastes accumulate further. Collings (1977) estimates its annual production to be about 350 million tons in Canada, with 140 million tons of this amount being produced in Québec. The environmental impact of surface mine wastes is disproportionately greater than the spatial extent would indicate, its influence extending beyond the boundaries of the mine.

1.1.1. The Environmental Impact of Surface Mine Wastes.

The environmental impact of surface mine wastes is multi-faceted.

Erosion, by both wind and water, is a common phenomenon of bare or thinly-vegetated mine wastes (Hall, 1956), with sandy or silty sites most susceptible, shales least (Knabe, 1965; Schessler and Droege, 1965). Particles of waste material, if dry and sufficiently fine, may be blown to surrounding areas in dry weather (Antonovics et.al., 1971; Peterson and Nielson, 1973; US Dept. of the Interior, 1967). This is of considerable concern when the particles are toxic, thereby endangering mine workers and local inhabitants, human and non-human, and destroying surrounding vegetation, further expanding the disturbed area. Irrespective of toxicity, wind-blown particles may damage nearby vegetation and inanimate structures via abrasion.

Wastes are often compacted by relevelling and the passage of heavy equipment (Beilby, 1956; Curtis, 1973b; Davies, 1956; Schessler and Droege, 1965), while soluble salts, if present, may form crusts (Peterson and Nielson, 1973). Where clays predominate, a dense panned horizon or surface layer may be produced (Ayerst, 1978; Beilby, 1956) or the fine particles may form a cohesive mass (Zimmermann and Moore, 1973). The paucity of organic matter, with its relatively low density and granulating ability, that is characteristic of many mine wastes contributes to their propensity to compaction. The resultant reduction in infiltration capacity promotes erosion via overland flow. Water erosion is further encouraged by the construction of steeply-sloped, unconsolidated waste piles. Strahler and Strahler (1974) estimate the eroded sediment yield from strip-mined areas to be up to 1,000 times that of comparable natural land surfaces, citing an example in Kentucky where waste piles yielded 27,000 tons of sediment per square mile over four years, while undisturbed forest produced 25 tons per square mile over the same time period. Waste sediment may enter local waterways, contributing to channel aggradation and augmented suspended load. Effects may be far-reaching. In addition to the physical damage to the aquatic milieu, including the burial of habitats, reduction of reservoir capacities and the filling of tidal estuaries (Antonovics *et al.*, 1971; Curtis, 1973b; Davies, 1956; Knabe, 1965; Strahler and Strahler, 1974; Watkin, 1975), its functioning is impaired. The increased turbidity reduces the penetration of incident solar radiation. As a consequence, primary productivity declines, with comparable repercussions on the higher trophic levels. The mineral balance of the water may also be altered, as dictated by the sediment composition.

The removal of overburden and waste rock, the excavation of ore deposits and the piling of wastes onto adjoining areas drastically alter the pre-existing topography and hydrology. Surface and subsurface drainage patterns are changed (US Dept. of the Interior, 1967). Water percolating through the wastes may become contaminated by acid formation. Sulphuric acid, for example, is produced by the oxidation of sulphur-bearing minerals, such as pyrite and iron sulphide, which are commonly found in mine tailings. This process, termed acid seepage, was recognized in several mining areas of Canada in the mid-1960's (Watkin, 1975). Similarly, contamination may result from the leaching of dissolved salts. Antonovics et al. (1971) claim that considerable pollution of waterways by dissolved heavy metals occurs in mine vicinities, with levels of 500 ppm being recorded. As well, the water reaction may be rendered excessively acidic or alkaline (Agnew and Corbett, 1973; Curtis, 1973a; Murray, 1977a; Strahler and Strahler, 1974). Overland flow may also transport contaminants from the wastes into nearby waters. Thirgood (1969) reports that "there are many instances" of mine wastes running directly into waterways, with consequent deterioration being inevitable.

Overloaded, oversteepened waste piles, if unconsolidated, may be unstable and subject to mass movement. When saturated by heavy rains or melting snow, the interface of the wastes and the original surface may become lubricated and the former liable to slide, particularly when the contact is on a steep slope. If present, a panned horizon may serve as a slipping plane (Beilby, 1956). The application of an amending material, eg. topsoil, upon the waste surface may, if structurally dissimilar, produce severe instability at the interface (Bradshaw et al., 1975). The saturation of clayey wastes may produce a slurry, which is liable to slide in an earthflow fashion, as illustrated by the 1966 Aberfan disaster, the flow of the colliery tip into the underlying valley having been precipitated by several days of heavy rain.

Surface mining disrupts pre-existing ecosystems. Vegetation is destroyed through physical uprooting or burial;

wildlife habitats are altered; migration routes may be transected and territorial ranges reduced. In addition, toxic elements may kill the flora and fauna outright or impair their growth and reproductive vigour. (Strahler and Strahler, 1974; US Dept. of the Interior, 1967)

The unnatural appearance of mine wastes devastates the aesthetics of the environs, particularly when occurring in otherwise undisturbed areas. In numerous instances, after the cessation of mining operations, the wastes become converted into unofficial garbage dumps, creating a health and safety hazard while further detracting from its appearance (US Dept. of the Interior, 1967). Thirgood (1969), for example, describes the detrimental health effects of the recreational use of the wastes of an abandoned, Saskatchewan arsenic mine.

1.1.2. The Influence of Vegetation on the Environmental Impact of Surface Mine Wastes.

The revegetation of surface mine wastes may attenuate the associated environmental degradation in a number of ways.

An established vegetative cover, particularly if dense, would anchor waste particles, especially the fine, blow-prone tailings material, reducing their susceptibility to wind erosion on drying (Shetron and Duffek, 1970; Watkin, 1975). A root mat stabilizes the substrate surface, while the plants themselves intercept moving particles. The effectiveness of vegetation in this regard is dependent on such factors as the rate and density of vegetative growth, particularly the root portion, and plant life form. In addition to providing a protective layer, the litter produced by a vegetative cover can truncate the saltation process. This is achieved by an increased proportion of falling grains landing on shock-absorbing bits of vegetation rather than on bare wastes, thereby preventing subsequent launchings (Russell, 1973). The stabilization of substrate structure reduces its liability to wind erosion. Decomposing plant debris yields various compounds, including free polysaccharide and polyuronide gums and water-proofing lipid components, which serve as bonding agents, thereby stabilizing structure (Broadbent, 1965; Murray, 1977a; Russell, 1971, 1973). To maintain this effect, though, the litter layer must be replenished as it decomposes. The establishment of windbreaks can reduce erosion by attenuating wind velocity. Russell (1973) has calculated that the distance over which a windbreak is effective in reducing wind speed at ground level is approximately 5 times its height on the windward side and 20-30 times on the leeward. Windbreaks require perforations so as to avoid the serious turbulence and resultant erosion caused by solid objects. Spence (1955) suggests that optimum efficiency is obtained with 50 % permeability and evenly distributed perforations. Belts of trees or hedges have been effectively employed to this end (Buckman and Brady, 1969; Chepil, 1949; Spence, 1955). However, as Russell (1973) states, vegetative windbreaks compete with adjacent plant life for the available resources (eg. water, nutrients), while altering the micro-climate through the provision of shade. The latter is not necessarily detrimental. For example, on lightly-coloured mine wastes, such as asbestos tailings, this would reduce the intense radiation occurring at the air-surface interface and moderate the diurnal heat flux. Though vegetation may diminish or prevent wind erosion, it suffers physically-damaging abrasion in the process.

A vegetative cover can also effectively reduce the susceptibility of the waste substrate to water erosion, whether through rainsplash or overland flow (sheetwash). A proportion of the precipitation may be intercepted and its kinetic energy absorbed, the amount varying with the vegetation density and plant morphology, especially leaf shape and inclination, as well as the duration of the rainfall. Thus, the throughfall, in the form of canopy drip or stemflow, produces less detachment of waste particles (Moore, 1978). Similarly, a vegetative ground cover, litter layer or organic mulch moderates the force of raindrop impact and resultant particle separation (Lal, 1976; Moore, 1978; Russell, 1973; Strahler and Strahler, 1974). Premature sealing is also avoided. An enhancement of infiltration capacity and substrate permeability can be effected by a vegetative cover directly, through the openings created by decaying roots (Strahler and Strahler, 1974) and the incorporation of organic matter (Russell (1973), as well as by the stimulation of the biological activities of the substrate flora and fauna (Lal, 1976). Should precipitation exceed the infiltration capacity, a vegetative cover can mitigate the erosivity of the resultant overland flow. The irregular surface of a vegetative ground cover and/or litter layer provides for depression storage, while reducing the velocity and dissipating the kinetic force of overland flow through friction (Lal, 1976; Moore, 1978; Russell, 1973; Strahler and Strahler, 1974). Grasses, due to their resilience and elasticity, as well as their dense root network, are frequently employed to control water erosion (Buckman and Brady, 1969; Strahler and Strahler, 1974). Chadwick (1975), for example, has observed that the runoff on bare colliery wastes is commonly triple that of comparable grasses areas. Trees can reduce water erosion under natural conditions given a sufficiently dense undergrowth and organic matter accumulation (Buckman and Brady, 1969). de Ploey et al. (1976) have demonstrated a counteracting influence of vegetative erosion control. On laboratory plots at $8\frac{1}{2}+^{\circ}$ inclination, erosion rates were higher on grass-covered samples than on bare. This was attributed to the "creation of turbulent eddies on the downslope side of the grass blades". While the application of this observation to field conditions may not hold, it does suggest that levelling may prove a beneficial preliminary to vegetation establishment. A patchy vegetative cover may be more detrimental than none at all since overland flow is then channeled between individual plants or clumps, with its erosivity thereby heightened. Progressive gullying may ensue.

A dense vegetative cover may improve resistance to mass movement, particularly the debris-avalanches and landslides to which surface mine wastes are prone if overloaded or oversteepened (Bishop and Stevens, 1964; Sharpe, 1938). This is largely achieved by the consolidation and stabilization of the substrate structure, as described in the preceding paragraphs. As well, the trunks and surface roots of established trees can arrest rolling stones in addition to intercepting smaller particles. Where saturation is a prerequisite to mass movement, the utilization of plants with high evapotranspiration rates may effectively reduce the water content of the substrate (Knabe, 1965). However, given the force of mass movement, vegetation is limited in its control. Often mechanical amendments, such as levelling, terracing, artificial drainage, reinforcement of slope bases or construction of restraining walls and check dams, would be required.

Numerous wastes contain potentially toxic concentrations of metallic ions, eg. nickel and chromium in serpentine-derived asbestos tailings and copper, lead, zinc and other heavy metals in their generic mine wastes. Upon decomposition, vegetation can have an ameliorating effect upon this toxicity. It is generally recognized that organic matter, in the form of humic colloids, can chelate metallic ions, producing stable compounds (Buckman and Brady, 1969; Hodgson et al., 1966; Knabe, 1965; Russell, 1973). However, the long-term effect of inactivating toxic metallic ions through chelation by organic matter, Weston et al. (1965) caution, is dependent on the stability of the complexes, in particular their maintenance until sufficient litter is produced to establish a "non-toxic rooting horizon". According to Russell (1973), the strength of absorption, and consequently the stability of the complexes, is as follows:

- trivalent iron and aluminum most strongly
- copper strongly
- cobalt, manganese, nickel and zinc more weakly.

Vegetation need not be in colloidal form to alleviate toxicities, however. Tolerant ecotypes have evolved and colonized such mine wastes, though species diversity and density are often poor. It has been demonstrated that comparable amounts of the toxic metal are absorbed by both tolerant and intolerant plants, with the metal being rendered innocuous within the former (Bradshaw _et al._, 1965). The incorporation of metallic ions into the living plant tissue reduces their concentration in the waste substrate. However, if the plant tissue is consumed, the metals are introduced into the food chain. As well, the metallic ions are again released to the substrate upon tissue decomposition. Over a prolonged period of time this process may entail the concentration of the heavy metals into the organic horizon(s), rather than their dispersal throughout the waste material. This may be beneficial if the metallic ions are totally inactivated through chelation, otherwise the enhanced toxicity may limit the biological activity of intolerant plants and animals. In vegetated sulphide-bearing wastes, Watkin (1975) hypothesizes that aerobic bacterial activity in the surface rooting region, supported by organic matter accumulation and vegetation stimulation, will remove oxygen before it encounters the underlying non-oxidized sulphide wastes. Acid formation would be reduced or eliminated.

While revegetation is unable to reproduce the pre-existing ecosystem, given the severity of the disturbance and the dissimilar environment of the wastes, it does serve as a pioneer sere in subsequent succession. Under natural conditions, the successful colonizers represent that subset of the seed rain that can tolerate the rigourous environmental conditions of the waste habitat. On observing the succession of mine areas in the Cologne Lignite District, Bauer (1973) found an initial low species diversity with patchy distribution, the pioneers forming "vegetational islands". They were thus not supplanted by subsequent invaders. Rather, the latter occupied the intervening space. The "community" was comprised of a mosaic of plant species, unlike natural associations. As the ecosystem developed, its species diversity exceeded that of the original landscape. Holland (1973) suggests that the community diversity of the revegetated wastes/natural landscape ecotone is beneficial to wildlife, particularly edge species. This would depend upon the quality of the wastes habitat. Artificial or aided revegetation accelerates the otherwise slow process of ecosystem development on surface mine wastes. Succession is not necessarily an orderly process. In addition to the natural disturbances to which it is subject, the developing ecosystem may be "suddenly displaced", to use Eyre's (1968) terminology, should it become economically feasible to mine the residual ore contained in the waste material.

While ameliorating the physical, chemical and biological characteristics of surface mine wastes, a vegetative cover, irrespective of its composition, enhances the aesthetic appeal by camouflaging the barren, irregular configurations of the waste material (Shetron and Duffek, 1970; Watkin, 1975).

1.1.3. The Environmental Factors Limiting the Revegetation of Surface Mine Wastes.

Numerous environmental factors, operating singly and synergistically, may impede the successful revegetation of mine wastes. Those most often cited are summarized in Table 1.1 and subsequently elaborated upon.

A. Physical factors.

  1. Colour: too dark, too light.
  2. Particle size: too coarse, too fine.
  3. Density: compaction, surficial cementation, panning.
  4. Stability: erosion, mass movement.
  5. Exposure: wind

B. Chemical factors.

  1. pH: too acidic, too alkaline.
  2. Nutrient status: low supply, low availability, toxicity.

C. Biological factors.

  1. Organic matter: insufficient amount.

Table 1.1. Environmental factors limiting the revegetation of surface mine wastes.

The surface colour of mine wastes indirectly affects vegetation through its influence on the absorption and reflection of solar radiation (albedo) and resultant ambient air and soil temperature regimes. Darker materials absorb and emit solar radiation to a greater degree than do light surfaces, causing wider diurnal temperature ranges (Richardson, 1958). This may restrict the establishment of sensitive, stenothermal species. Excessive absorption may raise the ambient substrate temperature intolerably, thereby "baking young plants and roots" (Murray, 1977a). Light surfaces have a high albedo. The resultant extreme radiation at the ground-air interface, in addition to high temperature, may inhibit seedling growth (Murray, 1977a; Zimmermann and Moore, 1973). Berg (1970) consistently recorded maximum surface temperatures of 50-55°C and 65-70°C on light (sandstone) and dark (coal) dry bituminous waste material, respectively, with ambient air temperatures of 30-35°C under intense solar radiation. Similarly, Schessler and Droege (1965) report that surface temperatures of 130°F (55°C) have been measured on darkly coloured shaly waste piles. While many wastes exhibit gray hues after drying and oxidation, those containing sulphide ore may develop reds, browns and/or yellows as oxidation progresses. Ogram and Fraser (1978), for example, found that the colour of high sulphide copper and zinc tailings changed from gray in fresh material to reddish brown upon oxidation. Asbestos and quartz-dominated wastes frequently become bleached upon drying, as confirmed by Moore and Zimmermann (1977) for asbestos tailings in southeastern Québec, with Munsell values of 2.5Y6/1 (gray) for moist and 2.5Y7/1 (light gray) for dry tailings. Coal mining produces a mosaic of waste material, including black and gray shales, buff sandstones and oxidized pyrites of red, brown and yellow (Berg, 1970; Cornwell, 1971).

Apart from the mechanical impediment (Black, 1968) and substrate stabilization afforded by larger particles (Knabe, 1965), the effect of particle size on plant growth is essentially indirect. As is generally recognized, coarse material, with a predominance of macropores, promotes rapid infiltration and percolation and maintains good aeration and gas movement. However, excessive leaching of nutrients and inadequate retention of water may ensue. Contrarily, in excessively fine material, dominated by micropores, water and air movement is severely impeded, the former largely restricted to capillary movement. This may be compounded by the high water holding capacity of colloids. Waterlogging inhibits root development and microbial activity. Anaerobic conditions are promoted. Archer and Smith (1972) suggest that plant growth is limited at air capacities less than 10 %. The critical value may be higher for agronomic species, which are often employed in the revegetation of mine wastes. For example, 15 % for wheat and oats and 20 % for barley and sugar beet have been cited (Kopecky, 1927, in Archer and Smith, 1972). Conversely, if infiltration is impeded, a droughty condition may prevail (Berg, 1975). Colloidal clays do possess a comparatively high cation exchange capacity, though this varies with the clay type (Buckman and Brady, 1969). While most plants do not require much soil in which to grow, the absence of soil-sized particles, i.e. less than or equal to 2 mm effective diameter, on some mine wastes hinders vegetation ecesis (Holland, 1973; Knabe, 1965) due largely to the poor water holding capacity (Schessler and Droege, 1965) and associated water deficiencies and nutrient losses through leaching as well as to inadequate anchorage. This state may be perpetuated by the ready erosion of the developing fine particles from unprotected sites. The particle size distribution of mine wastes is highly variable both within and between sites, as illustrated in Table 1.2.

	Tailings (43 sites)	Waste Rock (11 sites)	Overburden (8 sites)
% < 2mm	20-100 (148)	10-78 (67)	8-95 (91)
% sand	1- 97 (196)	35-99 (68)	20-93 (101)
% silt	0- 96 (195)	9-39 (57)	6-76 (102)
% clay	0- 40 (183)	1-29 (57)	1-37 (58)

Table 1.2. Particle size distributions of characteristic mine wastes. Numbers in brackets indicate the total number of observations. (after Murray, 1977a)

Desirable to a degree in droughty substrates in order to improve the water holding capacity (Archer and Smith, 1972) and reduce nutrient leaching, compaction, if excessive, is detrimental to plant growth. Roots may be unable to penetrate compacted horizons (McBryde, 1976; Murray, 1977a; Schessler and Droege, 1965; Zimmermann and Moore, 1973). Black (1968) has stated that roots, having pierced a hardpan, may be so constricted that death ensues due to inadequate water uptake. Surficial cementation can delay or prevent seedling emergence as seedlings may grow laterally in search of a weak point (Royle and Hegarty, 1977), with resultant morphological disfigurement or death. Where seeds have germinated on the surface, surficial compaction and crusting can hinder or preclude rooting with consequent dehydration. Shaykewich (1973) suggests that the confining stresses of some compacted soils are sufficient to impede the emergence of the embryo from the seed. With the reduction or elimination of macropores through compaction, the quality of the substrate aeration deteriorates and the oxygen supply declines (Beilby, 1956). Knabe (1965) suggests that inadequate amounts of oxygen in the presence of hydrogen sulphide can be lethal to trees and grasses. Surficial cementation decreases the infiltration capacity, with a consequent reduction in the soil water replenishment and a heightened susceptibility to erosion via overland flow (Davies, 1956; McBryde, 1976). A waterproofing phenomenon has been observed in some wastes (Knabe, 1965), with comparable effects.

As the surface horizon is generally more productive than the underlying substrate (Buckman and Brady, 1969), its removal via erosion leaves a residual material that is less amenable to plant growth than the original. However, deposits of eroded fine material provide an improved milieu due to an enhanced moisture and nutrient retention capability (McBryde, 1976; Schessler and Droege, 1965). Where revegetation has commenced, plants may be damaged by the removal of sediment from the rooting region in areas of erosion and burial in areas of deposition (Hall, 1956; Peters, 1970; Schessler and Droege, 1965). Mass movement may have a similarly destructive effect upon established vegetation. The development of the ecosystem is thus truncated.

Exposure to strong or consistent wind may physically damage plants through abrasion by wind-carried particles, ice-blasting, snow-cover redistribution or uprooting (McBryde, 1976; Murray, 1977a; Peters, 1970). Seedlings, in particular, are susceptible to dislodgement. Wind may desiccate plants by accelerating evapotranspiration, this effect increasing with the velocity and dryness of the wind (McBryde, 1976; Murray, 1977a). Wind-induced reductions in ambient air temperatures may have a debilitating or stimulating effect on plants, as dictated by their thermal requirements. Ecotypic adaptation to wind-exposed habitats has been documented for a number of species under both natural, eg. <u>Agrostis stolonifera</u> (Bradshaw, 1972) and artificial conditions, eg. <u>Zea mais</u> and <u>Helianthus annuus</u> (Whitehead, 1963). On mine wastes, exposure to wind can be expected on windward slopes and summits of waste piles, though, as Hall (1956) states, this would be modified in local depressions or in otherwise protected sites. Where levelling has eliminated windbreaks, wind velocity may accelerate with severe effects upon exposed plants. Unless dense, the pioneer plants of a mine waste, whether established naturally or artificially, are particularly susceptible to wind damage. A patchy vegetation cover affords little protection against wind. Until a dense vegetative cover is established, the waste particles are often highly erodible, with the particle content of the wind, and consequently its abrasiveness, comparably elevated.

It is generally recognized that pH, though rarely directly affecting vegetation, is of significant indirect consequence through its influence on the availability and uptake of plant nutrients and the activity of soil fauna. Phosphorus, for example, has a narrow availability range, becoming fixed in complex, insoluble compounds at pH less than 5.0 or greater than 7.0, whereas the availability of the other macronutrients is generally restricted only by moderate to strongly acidic conditions. At low pH, as well, such micronutrients as aluminium, copper, iron, manganese and zinc can become soluble in toxic concentrations, while at higher values, deficiencies may occur. Fungi, being faculative, can maintain themselves at all soil reactions, although they are more common at pH values less than 7.0. Bacteria and actinomycetes, including the nitrifiers, are generally inhibited by acid conditions. An important exception is Thiobacillus thio-oxidans, a participant in the sulphur cycle, the species functioning more effectively at low pH (Hesse, 1971). Van den Bergh (1969) suggests that germination and seedling establishment are particularly sensitive to pH. The reaction of mine wastes varies from acidic, eg. heavy metal or colliery spoils with oxidized sulphide (Berg, 1970; 1975; Chadwick and Salt, 1969; Ogram and Fraser, 1978; Tasker and Chadwick, 1978), to alkaline, eg. asbestos tailings (Moore and Zimmermann, 1977) and carbonaceous shale-dominated colliery wastes (Coaldrake and Russell, 1978). Unless modified artificially, the pH of non-sulphide mine wastes can remain relatively constant over time. For example, Moore and Zimmermann (1977) found the pH of asbestos tailings to have decreased by only 0.2-0.3 units after 60 years' exposure. However, wastes with sulphur-bearing minerals may become increasingly acidified as sulphide is oxidized (Peterson and Nielson, 1973). Ogram and Fraser (1978) observed a reduction in pH from 6.5-7.5 (fresh material) to 2.5-4.0 (oxidized material) in high sulphide copper and zinc tailings. Though recognizing it as a very slow process, Schessler and Droege (1965) suggest that weathering and leaching will remove significant amounts of acid-forming compounds, the products of sulphide oxidation.

Mine wastes are frequently deficient in N, P and K (Antonovics et al., 1971, Berg, 1975; Bradshaw et al., 1965; 1975; Chadwick, 1975; McBryde, 1976; Peterson and Nielson, 1973; Shetron and Duffek, 1970; Weston et al., 1965; Williams and Chadwick, 1977; Zimmermann and Moore, 1973). N, generally absorbed as NH_4^+ or NO_3^-, is a constituent of aminoacids, nucleotides and coenzymes, and a considerable portion, up to 70 %, of the total leaf N may be in chloroplasts. It also participates in the regulation of P and K usage. A deficiency of N interferes with protein synthesis and consequently with growth, particularly of the roots. P (HPO_4^{2-} or $H_2PO_4^-$) contributes to numerous enzymatic reactions, the vital ADP-ATP energy transfer, cell division, meristematic tissue development, flowering and fruiting, including seed formation. Metabolism and growth are disrupted by shortages, with a stunted morphology resulting. Berg (1975) suggests that seedlings are much more sensitive to P deficiency than are established plants. K (K^+) is important in the synthesis of amino acids and proteins, N transformations, anion absorption in roots, translocation and storage of carbohydrates and photosynthesis, through chlorophyll formation, though it is not a constituent of the plant fabric itself. Where sodium is excessive, K may attenuate its toxic effects. Deficiencies, as evidenced by leaf chlorosis, disrupt metabolic functions, retard maturity and increase susceptibility to disease and low temperature damage. (Buckman and Brady, 1969; Epstein, 1972; Hesse, 1971; Russell, 1973)

Many wastes are poor in organic matter and, when coarsely textured, are subject to high percolation rates. Consequently, the cation exchange capacity (CEC) is low and leaching, to which nitrate is particularly prone, may be severe (Bradshaw et al., 1975). A number of authors, however, do not consider low nutrient availability a critical limiting factor on mine wastes. For example, Schessler and Droege (1965) cite physical characteristics and pH as more important factors in determining revegetation potential since species with low nutrient demands can be employed, while legumes can gradually augment the N supply. However, as Bradshaw et al. (1975) suggest, legumes require careful management, with adequate P and Ca and restricted competition.

The Ca content of mine wastes varies. It is generally lacking or poor on acidic wastes, eg. sulphide ore mines, while sometimes excessive on alkaline wastes, such as limestone derivatives. Since Ca serves to detoxify other cations, a deficiency may permit these elements to accumulate to a harmful degree, thereby inhibiting growth. Stunted roots and leaf discolouration are symptomatic. As well, given its function in the growth of meristematic tissue and the mechanical strength of tissues, plant structure may be impaired by inadequate Ca. Excessive Ca may interfere with P and B nutrition, impair Mg and K absorption and induce chlorosis through reduced availability of Fe, Mn and Zn. (Buckman and Brady, 1969; Epstein, 1972; Heald, 1965; Hesse, 1971; Olsen, 1942, in Ramakrishnan, 1968; Russell, 1973)

On wastes of serpentinic or dolomitic origin, Mg may be overly abundant. High Mg concentrations have been shown to depress the development of primary phloem and to reduce root growth (Proctor and Woodell, 1975). In addition, excessive Mg may promote K deficiency (Epstein, 1972). Restrictively low Ca:Mg ratios, where insufficient Ca is present to attenuate the effects of Mg toxicity, are commonly found on these wastes (eg. Moore and Zimmermann, 1977).

Since many metals occur as sulphide ores, this nutrient, essential for N fixation, is rarely lacking, despite the paucity of organic matter (Antonovics et al., 1971). The oxidation of sulphur-bearing minerals, however, may produce sulphuric acid (Curtis, 1973a).

Heavy metals, including Cu and Zn on their generic wastes (Antonovics et al., 1971; Bradshaw et al., 1965; Holland, 1973; Knabe, 1965; Ogram and Fraser, 1978; Peterson and Neilson, 1973; Weston et al., 1965) and Ni and Cr on serpentinic wastes, such as asbestos (Moore and Zimmermann, 1977; Zimmermann and Moore, 1973), may be present in toxic concentrations. As a result, root growth is severely impaired, with laterals reduced to short stumps. Death frequently ensues. Ecotypes of several species, including *Agrostis* spp., *Festuca* spp. and *Deschampsia* spp., have evolved tolerance to high concentrations of the heavy metal(s) to which they are exposed. Antonovics et al. (1971) provide an extensive literature review on this phenomenon.

In addition to ameliorating structure and alleviating toxicity, organic matter darkens the substrate, reducing its albedo, of benefit on light-coloured mine wastes (eg. Zimmermann and Moore, 1973). It serves not only as a reservoir of exchangeable plant nutrients, but also as a major source of N, P and S (Broadbent, 1965; Buckman and Brady, 1969; Knabe, 1965; Murray, 1977a). Furthermore, acid humus may directly extract elements from minerals (Buckman and Brady, 1969). Organic matter also acts as a medium for microbial metabolism, being their primary source of energy (Buckman and Brady, 1969;

Knabe, 1965; Russell, 1973). On essentially all mine wastes, however, there exists a virtual paucity of organic matter unless artificially applied (Holland, 1973; Knabe, 1965; McBryde, 1976; Zimmermann amd Moore, 1973). Similarly, soil organisms, which benefit plants through their amelioration of the physical and chemical character of the substrate and the establishment of symbiotic relationships, such as that between mycorrhizae and plant roots, are generally absent (Holland, 1973; Knabe, 1965; McBryde, 1976; Murray, 1977a). Murray (1977a) suggests that in some cases adequate numbers of airborne microbes are introduced naturally, though often artificial inoculation is required.

1.2. Aim.

Broadly, this thesis examines the problem of establishing a dense vegetative cover on an unamended section of the iron tailings of Hilton Mine, Bristol-les-Mines, Québec. It is assumed that this is desirable so as to moderate the associated emvironmental deterioration.

Natural colonization has commenced. A single species, Salsola pestifer Nels., predominates, with other species being virtually non-existant, except for occasional, isolated individuals. Although S. pestifer is widely distributed on the tailings section, the percentage cover is low. Its density and vigour are variable, though consistently inferior to that indicated in the literature for this species on "normal soils". There exist, as well, ten bare patches, each with a minimum area of 25 m^2.

It is suggested that the establishment of an extensive, dense vegetative cover can be most readily achieved through the expansion and intensification of the local S. pestifer population. The rationale of its present micro-distribution must, therefore, be elucidated. To this end, the basic question - why are the bare areas uncolonized by S. pestifer - is addressed. Two hypotheses are proposed:

i. the bare areas are amenable to S. pestifer ecesis but have not received its seed;

ii. the bare areas have properties anatgonistic to S. pestifer ecesis.

The former incorporates the quasi-stochastic, though environmentally modified, element of seed dispersal. It implies that over a prolonged period of time a dense vegetative cover will be established naturally, the present patchy distribution being indicative of early succession. A conclusive test of the hypothesis cannot be effected given the constraint of a single growing season during which to conduct field research. The establishment of seed traps would not indicate the seed rain of the previous year and thus would not explain the present distribution of S. pestifer, given its annual habit, while additional field seasons would be required to adequately interpret the data obtained. An examination of the bare tailings for S. pestifer seeds would also be inconclusive. Their absence would not necessarily confirm the hypothesis. For example, seeds may have been present, germinated and died, the remains rotting, leaving no trace, or seeds (or seedlings) may have been removed or buried beyond emergence capability via an environmental agent. The hypothesis may be inferred, however, from a rejection of the second hypothesis.

The latter requires the identification of the specific limiting factors, which may be in the tailings material itself, exterior to it, or both. This cannot be achieved with absolute accuracy due to the quantity and complexity of the environmental parameters, operating singly and in combination, influencing vegetation ecesis and the attendant impossibility of examining all permutations. Logistical constraints are also imposed by available methodology. Strong suppositions can be postulated, however, through the coupling of selective physical and chemical analyses with growth experiments. That significant variations in substrate characteristics, i.e. sufficient to influence plant performance, can exist on a micro-areal scale has been previously demonstrated, eg. Downes and Beckwith (1951), Raupach (1951) and Snaydon (1962) for "normal soils" and Byrnes and Miller (1973), Cornwell (1971), Kimber <u>et</u> <u>al.</u> (1978) and Tasker and Chadwick (1978) for colliery wastes. As well, data compiled by Murray (1977a) illustrate the heterogeneous physical and chemical character of a number of Canadian heavy metal mine tailings.

2. Salsola pestifer Nels.

Although numerous scientific names have been applied to it (Bureau des Traductions, 1974), the species is usually referred to as Salsola pestifer Nels. or Salsola kali L. var. tenuifolia Tausch. Researchers have also employed, among others, Salsola kali var. tenuifolia Mey. (eg. Bailey, 1922; Gleason, 1963), Salsola tragus (eg. Bailey, 1917) and Salsola kali tragus (eg. Dewey, 1895). Salsola is generally thought to be derived from the Latin salsus, meaning salty, though disagreement has arisen as to whether this refers to the taste of the plant (Gleason, 1963) or to the habitats in which they grow (Bailey, 1922; Shosteck, 1974). Similarly, the specific notation kali is an arabic word for NaOH, while pestifer is a direct adoption of the Latin word for destructive, injurious or pestilential. The species is commonly called Russian thistle in English, though Russian cactus and Russian tumbleweed are sometimes applied, and chardon de Russie, herbe roulante, herbe roulante de Russie or soude de Russie in French (Bureau des Traductions, 1974; Frankton and Mulligan, 1970). Common saltwort, saltwort, soude commune and soude roulante generally refer to the closely related S. kali L. (S. kali L. var. kali), a native of coastal milieus.

S. pestifer is thought to have been first introduced into North America in 1873 in flax (Linum spp.) seeds imported from Russia and subsequently sown in South Dakota (Cave et al., 1936; Dwyer and Wolde-Yohannis, 1972; Larmour and MacEwan, 1938; Rousseau, 1968; Young and Evans, 1972). Although likely a native of Eurasia, Shosteck (1974) suggests that S. pestifer is not of specific Russian origin. Numerous authors have attested to the remarkable rapidity with which it spread upon its introduction (Dewey, 1895; Dalbis, 1921). Within 25 years its range included several Canadian provinces (likely Alberta, Saskatchewan and Manitoba) and 16 American states (Young and Evans, 1972). S. pestifer now extends into all of Canada, except Newfoundland and the northern territories, though it is considerably more abundant in the drier grassland regions of the Prairie provinces, in the East being confined largely to disturbed sites (Frankton and Mulligan, 1970). A similar distribution occurs in the U.S. (Kingsbury, 1964). The species has colonized a number of industrial wastelands, including foundry ash dumps in England (Clements and Ryves, 1972) and above-ground atomic bomb testing areas in Nevada (Wallace et al., 1968). While it has dominated the flora of the former for nearly four decades, it persisted in the latter for only a few years. Lindsay (1953) attributes the virtual restriction of S. pestifer to waste places outside of the prairies, its main geographic range, to "peripheral selectivity", whereby a plant may occupy a habitat which approximates that of its main geographic range or which compensates for altered conditions. Figure 2.1 illustrates the location of S. pestifer in the province of Québec, where the railroad has been "l'agent disséminateur par excellence" according to Rousseau (1968), who recounts that, for example, specimens were collected along a railroad near Sherbrooke as early as

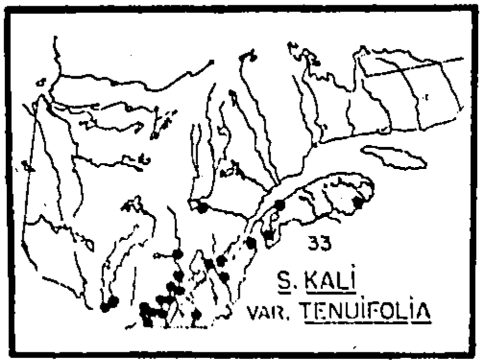


Fig. 2.1. The distribution of Salsola pestifer (S. kali var. tenuifolia) in the province of Québec. (Rousseau, 1968)

1904, while Dalbis, as reported in 1921, observed the species along railroad banks in Montréal and "quais" near Longueil. It is not clear whether the latter refers to railroad platforms or to river wharves.

S. pestifer reproduces by seed. No vegetative reproduction is known to occur in the species. With a single plant capable of producing as many as 200,000 seeds (Cave *et al.*, 1936; Young and Evans, 1972), S. pestifer enjoys a high reproductive potential. This potential is further heightened by its sophisticated dispersal mechanism. As the plant matures it dries and stiffens, while the lower branches curve inward, producing a somewhat spherical shape (Cave *et al.*, 1936; Frankton and Mulligan, 1970). Whether due to the decay of the base of the stem (Kerner, 1894, in Ridley, 1930) or to the phenological dehydration of the plant tissue, both of which reduce its resistance, the mature plant is severed at the ground line and readily rolled in the wind in a tumbleweed fashion, its seeds scattering in the process (Frankton and

Mulligan, 1970; Ridley, 1930; Young and Evans, 1972).

S. pestifer seeds may also be dispersed by other, more adventitious, means. Despite their poor performance in flotation experiments, Ridley (1930) maintains that the seeds can be dispersed fairly rapidly in moving water, with rivers, streams, irrigation channels, sewer systems and overland flow, including flooding, serving as dispersal agents. Debris, such as sticks, leaves or portions of the plant itself may act as a flotation device, though Guppy (1917) found that Salsola plant parts bearing fruit sank in 10 days. The spiny-tipped bracts enclosing the seeds may become entangled in the fur of passing animals. Numerous birds, eg. the Chukar partridge Harper et al., 1958), Gambel's quail (Campbell, 1957) and American mallard (Ridley, 1930), feed on S. pestifer seeds. While most seeds are likely destroyed in the digestion process, some may be ejected or regurgitated uninjured after departure from the feeding site. This often occurs when the individual has surfeited. Some seeds may fall from the beak while in transport. Further dispersal may occur through the death of individuals who have recently fed on S. pestifer, the seeds being released as the corpse decomposes. As with most weed species, S. pestifer seeds are dispersed by human activity and artifacts, including the movement of vehicles upon which the seeds have "hitchhiked", the use of contaminated seed mixes and the transport of ballast from infested areas.

The seeds of S. pestifer are small, each approximately 1-2 mm in diameter (Frankton and Mulligan, 1970; Wallace et al., 1968). If the conclusion of Rogler (1954, in Wiese, 1968) that, in general, seedling vigour is positively correlated with seed size can be applied to S. pestifer, one may infer that despite its prodigious seed production and effective dispersal, its distribution may be restricted by antagonistic environmental parameters, to which the seedlings, with little energy reserve in the seed, are particularly sensitive.

As reported by Rousseau (1968), the northern limit of S. pestifer in the province of Québec coincides with the 2250 growing degree day and the 18.5-23.5 kg cal. annual radiation balance isolines. Consistent with its use of the C_4 pathway of photosynthesis, the species obtains optimum growth and is most competitive with intense light (Welkie and Caldwell, 1970). Consequently, S. pestifer is likely restricted to open habitats with limited shade, particularly in the northern reaches of its range. There is some contradiction as to the temperature range in which the species is able to germinate. For example, Dwyer and Wolde-Yohannis (1972), in a New Mexico study, obtained germination within 7 days under a wide range of temperatures:

Temperature °C	% Germination	Temperature °C	% Germination	Temperature °C	% Germination
2	0.0	24	100.0	52	20.0
4	27.5	29	100.0	57	17.5
7	95.0	35	80.0	63	12.5
13	97.5	40	52.5	68	7.5
18	100.0	46	20.0	74	0.0

Wallace et al. (1968) in California, however, observed no germination at 10 °C or less and only some very delayed germination at 12 °C. At higher temperatures, 17-33 °C, total germination was "essentially equal", though the process proceeded more slowly at 17 °C. Subzero temperatures are inimical. Evans and Young (1972), for example, attribute the low rate of emergence of a set of S. pestifer seeds "solely to subzero night temperatures".

The drought-tolerance of S. pestifer is generally acknowledged. Coxworth et al. (1969) suggest that the water requirements of the species are one half to one third that of some of the common cereal crops. Dwyer and Wolde-Yohannis (1972) have produced a more specific comparison:

	Water use per g of shoot produced	
	at field capacity	at 0.01 available water level
S. pestifer	222 g (ml)	76 g (ml)
X̄ 4 grass species	1066 g (ml)	-
X̄ 4 shrub species	4644 g (ml)	-

Wiese and Vandiver (1970) observed that unlike other species studied, S. pestifer produced double the growth on dry* soil as on wet.** This is despite a relatively restricted, though rapidly developing, root profile, as illustrated in Table 2.1. Adequate moisture is required for germination, however, the process being prevented or arrested in progress when moisture is limiting (Wallace et al., 1968). In a field study, Evans and Young (1972) observed optimum seedling production among seeds germinating during a period punctuated by only 2 days of

* approximately wilting point ** approximately field capacity

	10 weeks		maturity			
	root profile area		root profile area	top growth		root area: top weight
	m^2	% mature		weight g	height cm	
Salsola pestifer	5.20	80	6.50	816	137	1:125
Amaranthus retroflexus	4.55	88	5.20	272	109	1: 52
Digitarius sanquinalis	6.50	74	8.73	91	91	1: 10
Kochia scoparia	5.76	61	9.48	771	170	1: 81
Solanum rostratum	5.57	76	7.34	272	84	1: 37
Sorghum	3.16	49	6.50	136	97	1: 21
Tribulus terrestris	4.46	41	10.78	272	137	1: 25
Xanthium pennsylvanicum	7.25	40	17.93	590	152	1: 33

Table 2.1. Comparative root and top growth of a number of species, including *S. pestifer*. (modified from Davis *et al.*, 1967)

dryness, while significantly fewer seedlings were produced during drier periods. Similarly, Young and Evans (1972) found germination to increase with rising relative humidity. A number of authors have suggested that the relegation of S. pestifer to dry habitats is due to its inferior competitive ability on more generally favourable sites (Dwyer and Wolde-Yohannis, 1972; Larmour and MacEwan, 1938; Wallace, 1970).

Compacted soils are particularly detrimental to the establishment of S. pestifer. In separate experiments, for example, Evans and Young (1972) and Wallace et al. (1968) found that despite the high germination rate of seeds sown on the surface of compacted soils (80-100%), virtually total mortality from dehydration occurred, the seedling root tips having been unable to penetrate the soil. As with other species, the emergence of S. pestifer seedlings may be comparably thwarted.

As a halophyte, S. pestifer is salt resistant and consequently tolerates alkaline conditions (Dwyer and Wolde-Yohannis, 1972; Smith et al., 1975).

In relation to mine wastes revegetation, a test plot study carried out by Blakeman (1976) on the tailings of Hilton Mine found S. pestifer to be "the most successful" of the 15 species employed. S. pestifer had i) attained an average height of 12 inches, ii) occurred in 80% of the total row lengths, iii) exhibited a high rate of germination (the only species to do so), and iv) achieved the most widespread distribution of well-developed plants. While the tailings utilized in the plot study "are not typical of the entire deposit", the superiority of S. pestifer would suggest it deserving of consideration in mine wastes revegetation efforts.

The advantages of securing a vegetative cover upon a mine wastes site must be weighed against the negative aspects of the species employed. The former, as regarding S. pestifer, includes the stabilization of the waste material by its rapidly developing root system and the retardation of air and water erosion through the interception of substrate particles, to which its densely-branched morphology particularly lends itself. The species copious seed production and efficient seed dispersal mechanism would accelerate revegetation. Also, as Blakeman (1976) suggests, its rapid early growth would protect more slowly developing seedlings from sandblast while providing shade. As previously noted, S. pestifer seeds are consumed by a number of bird species. In addition, several authors have reported its use as forage, often in times of drought (Cave et al., 1936; Dwyer and Wolde-Yohannis, 1972; Larmour and MacEwan, 1938; Uphof, 1968; Wallace, 1970). Larmour and MacEwan (1938) found its composition at maturity to be comparable to alfalfa hay and its roots similar to oat straw. It may, therefore, be a suitable food source for wild herbivores, although Kingsbury (1964) cautions that S. pestifer may contain amounts of soluble oxalates dangerous to non-ruminants and occasionally toxic levels of nitrate, though the latter is unlikely on N impoverished soil. S. pestifer may serve as a feeding and/or breeding host for a number of insects and disease or parasite vectors (Goeden, 1968; Smith et al., 1975; Wallace et al., 1968). Given its tumbleweed-like behaviour, plants of this species may obstruct roadways and water channels, including irrigation ditches, bury fence rows and, when desiccated, pose a fire hazard (Wallace et al., 1968).

3. The Geographic Setting.

The Hilton Mine ($45^{\circ}30'$N, $76^{\circ}20'$W) is located at Bristol-les-Mines in southwestern Québec, approximately 80 km west of Hull-Ottawa along the Ottawa River and 3 km inland of Baie du Chat (Fig. 3.2.). At the mine site, the study area consists of a strip of unamended tailings, ranging between 25-75 m in width, encircling a tailings pond. It is itself surrounded by a more extensive expanse of amended tailings material (Fig. 3.1.).

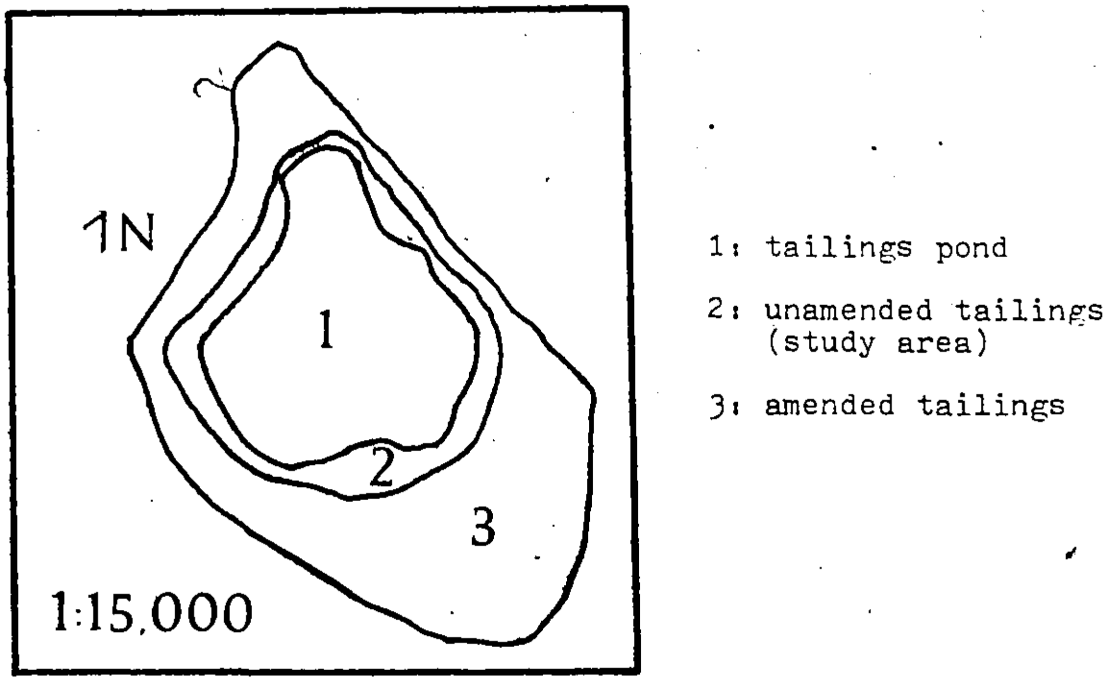


Fig. 3.1. Map of the tailings area.

The climate of the study area can be classified as Dfb in the Koppen-Geiger system, D indicating a snow climate with the warmest month mean over 10 °C and the coldest month mean under -3 °C, f sufficient precipitation in all months,

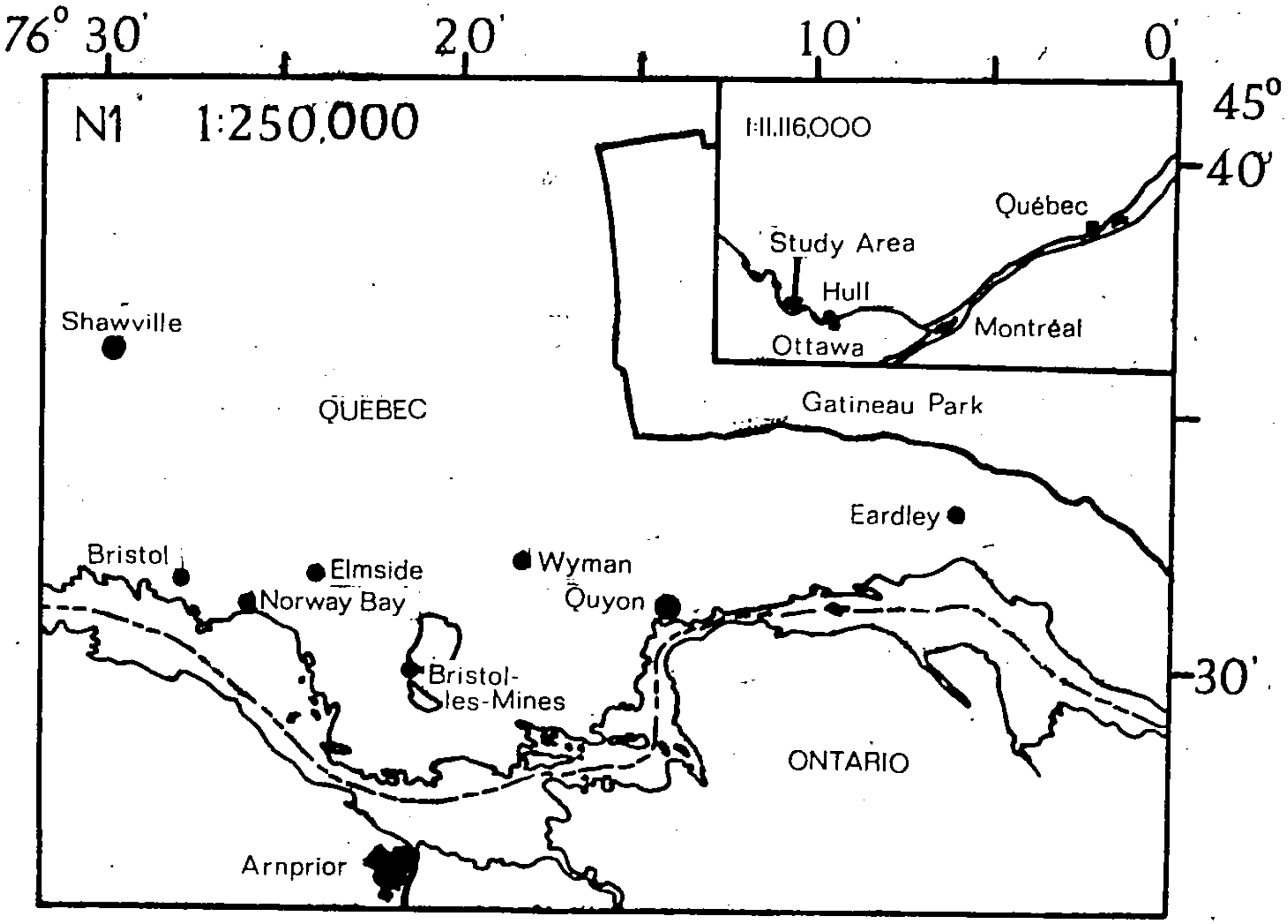


Fig. 3.2. Location map of southwestern Québec and adjacent Ontario.

and b the warmest month mean less than 22 °C with at least 4 months having means over 10 °C (Strahler, 1973). This is confirmed by the available meteorological data (Table 3.1). Although there is no meteorological station at Bristol-les-Mines, the prevailing conditions can be inferred from data obtained at Shawville ($46^{\circ}36'$N, $76^{\circ}30'$W), approximately 15 km to the northwest. While there exists a station closer to the mine site, located at Arnprior-Grandon, the data available are patchy and normals have not been calculated. The Shawville data are not comprehensive, and so have been supplemented with information derived from national climatic maps, though the inexactitude of the latter, given their large scale, is recognized.

Sabourin (1965), in accord with Wilson (1926), suggests that the study area lies in an overlapping border zone between the St. Lawrence Lowlands and the Laurentian Uplands of the Canadian Shield, given the outcropping of Precambrian rocks, the overlaying of Precambrian formations by Paleozoic strata and the presence of Champlain Sea sediments, which fill many depressions, thereby producing the physiographic appearance of the Lowlands. This supposition is supported by the mineral make-up of the mine area, which is predominantly magnetite in granite (Precambrian Post-Grenville intrusions of biotite granite and granite gneiss), with limestone (Grenville series crystalline limestone) and dolomite (Paleozoic Ordovician Beekmantown dolomite) (Collings, 1977; Sabourin, 1965). According to data derived from aerial photography and field recon-

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Daily temp $^{\circ}$C*													
X̄ maximum	--6.9	- 5.2	1.3	10.2	17.8	23.1	25.6	24.1	19.5	13.3	4.4	--4.4	10.2
X̄ minimum	-17.9	-17.7	-10.4	- 1.7	4.2	10.2	12.5	10.6	6.2	1.2	- 4.0	-13.8	- 1.7
X̄ mean	-12.4	-11.4	- 4.6	4.2	11.0	16.7	19.1	17.4	12.9	7.3	0.2	- 9.1	4.3
Precipitation**													
X̄ rain mm	15.0	9.9	24.1	55.9	71.9	72.9	89.1	68.6	90.7	65.3	56.1	28.2	647.7
X̄ snow cm	41.4	42.9	27.2	4.8	0.3	0.0	0.0	0.0	T	1.3	18.0	50.8	186.7
X̄ total mm	56.4	52.8	51.3	60.7	72.2	72.9	89.1	68.6	90.7	66.6	74.1	79.0	834.4
# days with meas rain	2	1	4	8	9	10	10	9	10	9	8	3	83
# days with meas snow	11	10	6	2	T	0	0	0	T	T	5	12	46
# days with meas precip	13	11	10	10	9	10	10	9	10	9	13	14	128
X̄ growing season days***													190
X̄ growing degree days***													3150
X̄ frost free period days***													150
X̄ daily net radiation 1/day***	-17.5			137.5			237.5			62.5			
X̄ net radiation***													42.5

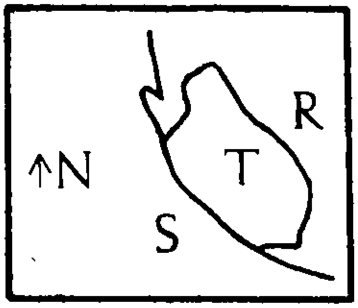
Table 3.1. Meteorological data for Shawville, Québec.

* Environment Canada, 1978.

** Environment Canada, 1973.

*** Phillips, 1974.

naissance, the tailings of Hilton Mine border an earthflow-prone area of sand known or suspected to overlie sensitive clay of Champlain Sea origin (Fransham <u>et al.</u>, 1976) (Fig. 3.3). The mineralogy of the tailings themselves is given in Table 3.2.



R: bedrock and/or till and/or gravel; predates the sensitive clay; includes material with no association with the marine submergence as well as contemporaneous gravels and sands.

S: sand known or suspected to overlie sensitive clay; 2-4 m deep; consists of fluvial or deltaic deposits of proto-Ottawa R.; contemporaneous with the marine submergence.

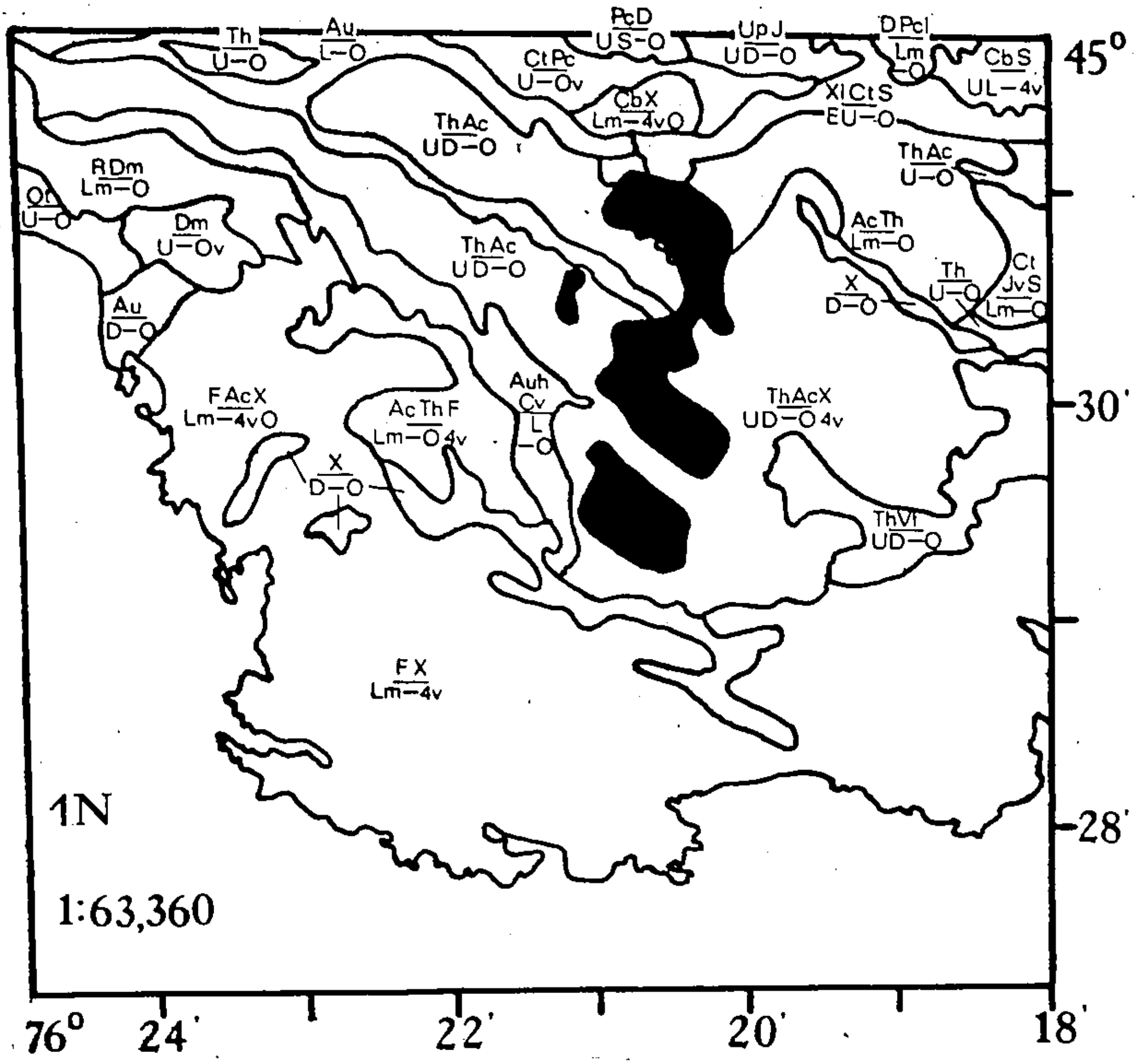
T: tailings of Hilton Mine.

Fig. 3.3. The distribution of sensitive clay in relation to the tailings of Hilton Mine. (after Fransham <u>et al.</u>, 1976)

Constituent	Formula	%
Amphibole (actinolite)	$Ca_2(Mg,Fe'')_5(Si_8O_{22})(OH,F)_2$	>20
Quartz	SiO_2	>20
Calcite	$CaCO_3$	10-20
Serpentine	$Mg_6Si_4O_{10}(OH)_8$	10-20
Talc	$Mg_3Si_4O_{10}(OH)_2$	10-20
Mica (muscovite)	$K_2Al_4(Si_6Al_2)O_{20}(OH,F)_4$	10-20
(biotite)	$K_2(Mg,Fe'',Fe''',Al)_6(Si_{6-5}\text{-}Al_{2-3})O_{20}(OH,F)_4$	10-20
Plagioclase (albite)	$NaAlSi_3O_8$	<10
K-feldspar (orthoclase)	$KAlSi_3O_8$	<10

Table 3.2. The mineralogy of the iron tailings of Hilton Mine. (after Collings, 1977; Whitten and Brooks, 1974)

The landscape varies from relatively level with micro-relief to undulating (Fig. 3.4). There exist as well areas of



Soil Name
Topography – Stoniness

Topography	Stoniness
D: depressed land	O: stones & outcrops absent
E: steeply sloping banks	4: excessively stony
L: level land	Ov: stones absent, some outcrops
Lm: level land with microrelief	4v: excessively stony & rocky
U: undulating land	
S: gently sloping land	

Symbol	Soil Name	Great Soil Group	Texture	Drainage	Parent Material
Ac	Achigan	Podzol	Loamy fine sand	Imperfect	Fine sand over marine clay
Au	Alluvium-undifferentiated	Recent alluvium	Sandy surface	Variable	Stratified recent alluvium
Auh	Alluvium-undifferentiated	Recent alluvium	Clayey surface	Variable	Stratified recent alluvium
Cb	Saint-Columban	Podzol	Stony sandy loam	Good	Non-calcareous till
Ct	Coteau	Podzol	Very fine sandy loam	Good	Sandy loam over marine clay
Cv	Courval	Dark gray gleysolic	Sandy loam	Poor	Shallow sand over marine clay
D	Dalhousie	Dark gray gleysolic	Clay loam	Imperfect	Clay
F	Farmington	Lithosol-Brown forest	Loam	Good to poor	Shallow till on calcareous rock
J	Saint-Jude	Podzol	Sand	Imperfect	Medium to fine sand over marine clay
Jv	Saint-Jovite	Brown podzolic	Very fine sandy loam	Good	Eolian material on till
Ot	Ottawa	Recent alluvium	Sand	Excessive	Recent sandy alluvium
Pc	Pontiac	Podzol-Brown podzolic	Silt loam to silty clay loam	Good	Shallow silt over clay
Pcl	Pontiac	Podzol-Brown podzolic	Loam	Good	Shallow silt over clay
R	Sainte-Rosalie	Dark gray gleysolic	Clay	Poor	Gray marine clay
S	Soulanges	Podzol	Fine to very fine sandy loam	Imperfect	Sandy loam and silt over marine clay
Th	Saint-Thomas	Podzol	Fine to very fine sand	Excessive	Fine to very fine sand over marine clay
Up	Uplands	Podzol	Sand	Excessive	Medium sand
Vf	Vaudreuil	Gleysol	Very fine sand to fine loamy sand	Very poor	Shallow sand over marine clay
X	Swampy land	-	Variable	Very poor	Variable
Xl	Landslides, escarpments & gullies	-	Silty surface	Variable	Landslides & ravines

Fig. 3.4. Soils map of the Bristol-les-Mines vicinity, with topography and stoniness indicated. (after Lajoie, 1962)

depressed land, which are usually associated with marsh. The topography has been markedly altered at the mine site through the creation of a deep open pit, tailings ponds and waste piles (Fig. 3.5). The study area itself consists of fairly level tailings, laced with a patchwork of microrelief, falling abruptly into the enclosed pond, the mean slope of the bank being approximately 45°. The width of the shore exposed during the summer ranges from 1 to 50 m, though generally it is 1-2 m on the north, south and west sides and 10-15 m on the east, the extreme width occurring in the northeast corner and to a lesser degree in the southwest. The clay-dominated upper tailings on the east side are cut

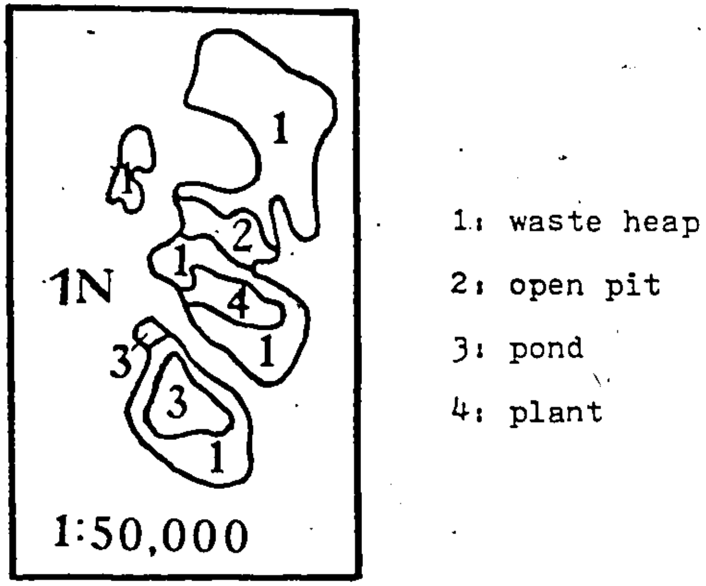


Fig. 3.5. Topography of the mine site.

by several sizeable gullies, greater than 1 m in depth and width, meandering eastward tens of metres. Another occurs in the sands of the southwest corner. A number of much smaller gullies, generally less than a cubic metre in size, have eroded sections of the bank on the north, south and east.

As illustrated in Fig. 3.4., numerous great soil groups are represented by the soils of the Bristol-les-Mines vicinity - podzol, recent alluvium, dark gray gleysolic, lithosol, brown forest, brown podzolic and gleysol. In addition, there are sizeable expanses of swampy land, particularly to the south, as well as limited areas of undifferentiated, stony land and landslides, escarpments and gullies. The drainage, which varies from very poor to excessive, does not appear to be consistent with either the texture or the parent material, the former ranging from clay to loam to sand, the latter including alluvium, till and marine clay overlain by sand of variable depth and fineness.

The natural vegetation is mixed coniferous-deciduous forest, including *Picea mariana*, *P. glauca*, *Larix laricina*, *Abies balsamea*, *Thuja occidentalis*, *Fraxinus nigra*, *Ulmus* spp., *Salix* spp. and *Populus tremuloides* (Lajoie, 1962). Much has been removed, however, for the establishment of farms.

At the mine site, levelled waste rock piles have been colonized by such crop species as *Melilotus* spp., *Phleum* spp. and *Bromus* spp., seeded during a reclamation project initiated in 1971. Test plot studies concerning the revegetation of the tailings were carried out in 1973 and in 1976. The former was expanded to a full seeding program using oats, chemical fertilizer and manure. The latter employed *S. pestifer* as well as 14 other species, including legumes, grasses and herbs, growing on 13 tailings deposits in eastern Ontario and southwestern Québec (see p. 33). (Blakeman, 1976)

A further revegetation effort was undertaken on the area designated "amended tailings" in the current study. The process involved the sowing of a commercial seed mixture of agronomic species and the application of fertilizer and barnyard manure. The species included S. pestifer, Atriplex spp., Chenopodium spp., Polygonum aviculare, Artemisia vulgaris, Cirsium spp., Poa pratense, Bromus spp., Phleum pratense, Hordeum jubatum, Medicago sativa, Melilotus alba, M. communis and Trifolium pratense. This was effected on the north side in 1976, the west in 1977 and both the south and east in 1978, with no area receiving more than one treatment. A reconnaissance in May, 1979 found the existing vegetation to be very scarce on the north side; of variable performance on the west; dense, diverse and vigourous on the south; and patchy and chlorotic on the east. By August, 1979, many individuals were dead or severely desiccated, which may have resulted from the extreme heat and aridity of the preceding months. Similar species growing on non-tailings soil in the vicinity were not so afflicted, however. The S. pestifer plants on the study area strip did not appear to be adversely affected.

Originally known as the Bristol Mine, exploitation of the iron reserve here first began in 1872. Operations ceased, however, in 1894, resuming only in early 1958. The mill, located at the mine site, had a capacity of 7,000 tons per day. Due to the exhaustion of the reserve, mining was discontinued in early 1977. (Collings, 1977; Sabouring, 1965)

4. Methods.

4.1. Field Work.

Though two preliminary reconnaissances were effected, May 10 and June 20, 1979, the field work proper was executed during August, 1979, as the vegetation would then be at its maximum vegetative growth despite some natural variations in germination time. The site was again visited on October 14, 1979 to collect the matured seeds for subsequent laboratory growth experiments.

The sampling strategy employed consisted of establishing a 5 m x 5 m square grid on 10 bare and 10 vegetated sites. These were subjectively located so as to maximize the between group heterogeneity within each set of 10 plots and to minimize the variation within each bare-vegetated pair. This would reduce

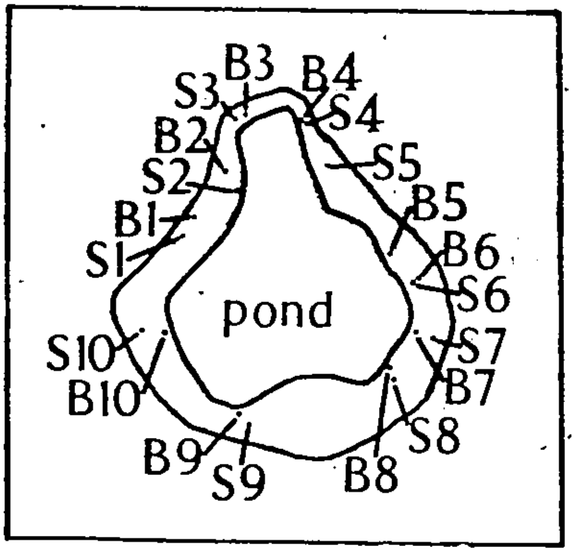


Fig. 4.1. Sample plot locations.

if not eliminate, spurious differences between overall bare and vegetated characteristics, while ensuring adequate sampling of the site variability. A site was termed bare if it was devoid of vegetation over a minimum area of 25 m^2, while the presence of at least 25 individual plants over a comparable spatial extent constituted a vegetated site. Only Salsola pestifer occupied the vegetated plots. This reflects the low occurrence of other species rather than deliberate sampling design. Within each grid, 8 points were randomly located, using a 0.5 m interval. It was thought that this combination of subjective and random sampling would better represent the site variation than would a single random, systematic or derivative strategy, while the option of effecting statistical tests of significance was retained. Within each vegetated plot, an additional 8 points were located using the technique employed by Snaydon (1962) and Tasker and Chadwick (1978). Accordingly, if the original random point fell on a vegetated section, i.e. within 25 cm of a S. pestifer individual, the nearest bare tailings, minimum 25 cm x 25 cm in area, was also sampled. Conversely, if the original point fell on a bare section, the procedure was reversed (Fig. 4.2). In both cases a minimum boundary of 25 cm between the vegetated and bare points was maintained to reduce the effects of plant-soil interactions on the latter. The distance between each pair of vegetated and bare samples was recorded. In total, 240 points were sampled - 80 bare from completely bare plots (designated B), 80 bare from vegetated plots (S-) and 80 vegetated also from vegetated

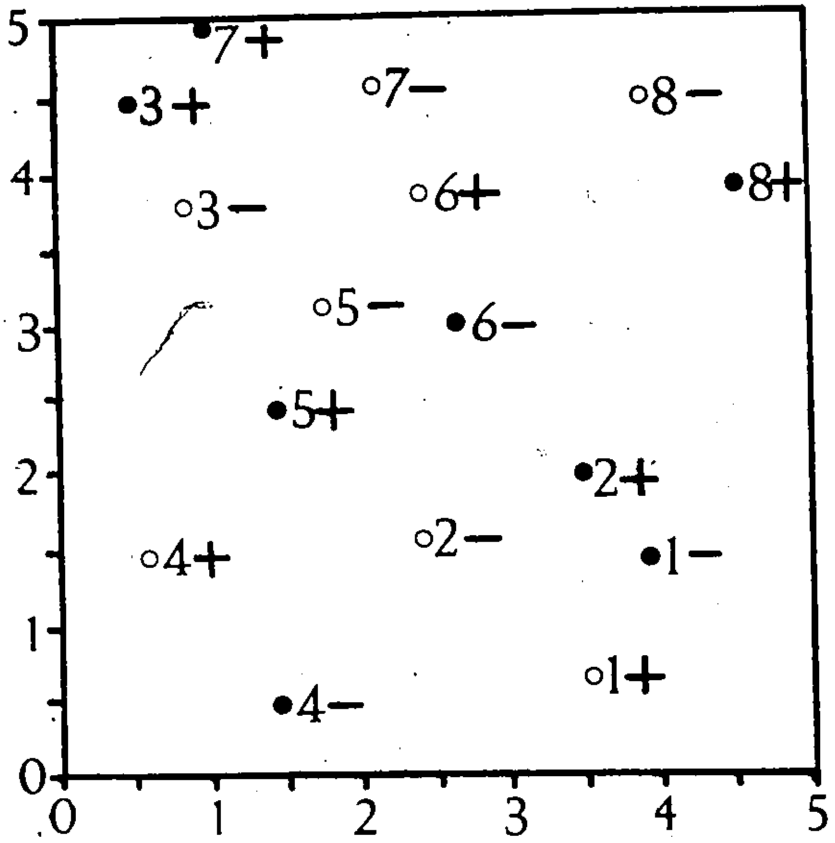


Fig. 4.2. Illustration of the vegetated plot sample location technique. • : original point; ∘ : derived point.

plots (S+). Thus, the sampling design permitted the comparison of bare and vegetated tailings on two areal scales.

At each of the B and S- points, microtopography was described and a "soil" sample, approximately 10 cm in diameter and 10 cm in depth, was collected. At the S+ points, a 25 cm x 25 cm square quadrat was centred about the S. pestifer individual. Within each quadrat i) the total number of individuals, ii) the percentage cover and iii) the distance between the central S. pestifer and its nearest neighbour were measured. The microtopography was also described. Soil samples were collected from beneath the central S. pestifer plants, which were also taken for dry weight determinations.

Although differential surface compaction was observed measurements were not effected due to the unavailability of a penetrometer. Climatic data were not collected. Since the study area is of limited spatial extent, large-scale climatic variation is unlikely, while micro-climatic differences can be inferred from microtopography description. As well, plant distribution dynamics are often influenced by preceding climatic events rather than, or in addition to, prevailing conditions. Selectivity was necessary due to the restrictions of limited time and manpower. Consequently, attention was directed predominantly to the analysis of the tailings material itself. Since it originates from an ore deposit, it seems unlikely to be a benign growth medium, but rather to possess properties limiting vegetation ecesis. As well, the chemical ore separation process may have introduced antagonistic elements. This approach is supported by the mine waste revegetation literature.

4.2. Laboratory Work.

4.2.1. Physical and Chemical Analyses of the Tailings.

A subset of 120 tailings samples was randomly selected, 4 from each group of 8. These were air-dried and then subjected to the following analyses:

i) The presence of free carbonates was confirmed through the application of a few drops of 1N.HCl to approximately 3 g of tailings. This is of importance regarding the selection of appropriate techniques for the determination of P and exchangeable Ca and Mg.

ii) Colour, dry and moist, was described according to Munsell notation. It was thought preferable to obtain the colour values in the laboratory where the degree of soil moisture could be better controlled.

iii) Compaction of the tailings employed in the growth experiments was ascertained subjectively by trying to move the surface material with a pen top using as near as possible constant pressure. The two groups - uncompacted and compacted - could be readily differentiated. The results accorded very well with the particle size classes determined <u>in situ</u>, the clays tending to be compacted, the sands and silts not. The test was carried out 6 weeks (± 1 or 2 days) after the commencement of the particular growth experiment as those tailings liable to compaction would have done so by then. It also provided some between experiment control.

iv) pH was determined in a 1:1 volume paste with distilled water.

v) Available P was obtained colorimetrically by the dilute acid fluoride method (Olsen and Dean, 1965). While this method may overestimate the P content of calcareous soils, through the excessive dilution of calcium phosphates, this is unlikely to be significant given the low P content indicated by the geology of the tailings.

vi) Exchangeable Ca, Mg, K and Na were initially measured by extracting 5 g of tailings with 50 ml of 1N ammonium acetate (pH 7.0) and analysing the solution on a Perkin-Elmer (model 403) atomic absorption spectrophotometer. The extracts were diluted with 0.2% La solution for the Ca and Mg determinations in order to reduce ionic interference, while distilled water was used for K and Na. Where $CaCO_3$, $MgCO_3$ and gypsum are present in significant quantities, NH_4OAc is considered an unsuitable extractant due to its solvent effect on the former, which produces erroneous exchangeable Ca and Mg values (Bower et al., 1952; Chapman, 1965; Hesse, 1971; Proctor, 1971). Given the geology of the tailings and the positive results of the free carbonate test, the exchangeable Ca and Mg of a 30 sample subset were reanalysed, substituting the NH_4OAc with NaOAc (pH 8.2), which has a significantly lower solvent effect on carbonates (Table 4.1).

Carbonate	N.NaOAc (pH 8.2)	N.NH_4OAc (pH 7.0)
calcite	1.62 meq/l	17.10 meq/l
dolomite	0.75 meq/l	9.40 meq/l
magnesite	0.15 meq/l	1.44 meq/l

Table 4.1. Solubilities of carbonates in sodium and ammonium acetate. (after Bower, 1952)

It was considered necessary to have reliable Ca, Mg K and Na data since a number of factors indicated that their absolute and relative values may be influential. The mineralogy of the tailings, as reported by Collings (1977), particularly amphibole, serpentine, talc and mica (biotite), suggest a preponderance of Ca and Mg. Since the four major base cations are known to interact (eg. Epstein, 1972), a comparative excess of one or more may have repercussions on plant growth. The percentage figures of 5.38 and 19.04 for CaO and MgO, respectively, also quoted by Collings (1977), represent a 1:3.5 ratio. As these are oxides, the ionic milliequivalent ratio would be more extreme. In numerous studies of serpentine flora, an excess of Mg over Ca has been cited as a predominating limiting factor. S. pestifer is a halophyte. As it is the sole colonizer of the tailings strip, Na may be influential.

Although desirable to effect nutrient analyses of plant tissue so as to compare concentrations with the underlying tailings, this was not possible given the life cycle strategy of S. pestifer. Individuals of this species lose their leaves prior to and during flowering. During the sampling period, some plants had commenced this shedding. Since a number of nutrients, including N, Fe and Mg, are concentrated in leaf tissue, valid nutrient contents and subsequent comparisons could not be obtained.

The number and type of analyses carried out must necessarily be restricted. Iron was not measured due to the uniformly alkaline character of the tailings samples, excluding a number of the idiosyncratic plot B2 samples. Under alkaline conditions, iron is precipitated and rendered insoluble. As well, much of the original magnetite, itself a relatively insoluble mineral, has been extracted. Insufficient N, particularly as NH_4^+ and NO_3^-, is often a limiting factor on mine wastes. However, its measurement is subject to considerable imprecision (Bremner, 1965) and micro-scale comparisons would consequently be untenable. Organic matter was obviously lacking throughout the tailings strip and so was not quantified. In the field, three particle size classes - sand, silt and clay - could be readily determined visually and manually. There was no differentiation in vegetation according to particle size class, however, plots of each class being as often vegetated as bare. Consequently, a more refined assessment was not effected.

4.2.2. Growth Experiments.

The growth chamber used in the five experiments consisted of wooden, enamel-painted trays placed on two open-sided shelves, each under four pairs of fluorescent growth lights. Until December 11, constant lighting was maintained. Wallace *et al.* (1968) found *S. pestifer* did not need darkness for germination. This was then altered to a 12/12 light/dark schedule to accommodate the requirements of another non-associated experiment, conducted simultaneously by another researcher. Within 6 weeks the former was again enforced due to the mechanical failure of the automatic timer and the inability to maintain the schedule manually. It is recognized that this does not simulate the light duration of a temperate region growing season. However, the extended artificial daylength may compensate somewhat for the lower than natural light intensity in the growth chamber. It is hoped that the effect on the plants of the shortened simulated daylength during the enforcement of the 12/12 schedule and of the alteration from one regime to the other was uniform, and the reliability of the experiment results not jeopardized. Air temperature was 21-23°C.

Except in the germinability experiment, only seeds from vigourous plants in the productive S8+ plot were employed. This afforded some control of the seed variability, though the heterogeneity of seed size and vigour even on a single plant precludes absolute control. In these experiments, 5 seeds were sown per pot, in a die-face formation, i.e. ⁙. Each pot was regularly rerandomized and was rotated 90° after each watering in order to reduce photo-tropism. The pots used in the inundation experiment were the standard 3-cornered, clear plastic laboratory containers, with volume levels indicated at 30 cc intervals, while dark green, 7.5. cm diameter plant pots were utilized in the latter 3 experiments. The seeds were not stratified as Young and Evans (1972) had observed no response to pre-chilling prior to testing in S. pestifer.

4.2.2.1. Germinabilty.

Twenty-five seeds from each vegetated plot were placed on 9 cm, number 4 filter papers lining the bottoms of 10 petri dishes. The petri dishes were then inundated with tapwater, covered with clear plastic tops and randomly placed in the growth chamber. The experiment lasted 2½ weeks, December 5-21. It was terminated at this time because no new germination had been observed since December 15 and a number of seedlings had begun to rot. Only the number of germinated seeds was recorded as the aim of the experiment was merely to ascertain whether or not the seeds were viable and germinable, i.e. ready for experimental manipulation. A seed was considered germinated when the radicle had uncoiled to at least 2 mm.

4.2.2.2. Inundation.

Given their location between the base of the bank and the edge of the tailings pond, a number of bare plots (B4, B7, B8 and B10) may be subject to seasonal inundation, due to the rise in the level of the tailings pond induced by spring snowmelt. Consequently, a growth experiment was devised to test this effect on the germination and survival of S. pestifer It consisted of 3 inundation time periods - 0 weeks (T_0, the control), 2 weeks (T_2) and 4 weeks (T_4); 2 substrate materials - sand and vermiculite; and 3 depths of seed sowing - surface, 1 cm and 2½ cm. There were four replications of each permutation. The vermiculite, though dissimilar to the clay-dominated tailings in particle size, is likely comparable in moisture retention capability. The appropriate dry substrate material was placed in each pot to the 150 cc mark. Drainage holes were melted into the bottoms of the 24 control (T_0) pots. In total, there were 72 pots and 360 seeds. During the first two weeks, the T_0 pots received 100 ml of tapwater every 4 days, while the T_2 and T_4

pots were watered until the water level reached the 210 cc mark. This was done every 2 days to maintain inundation in the dry laboratory environment. After 2 weeks, drainage holes were melted into the T_2 pots and these subsequently received the 100ml/4day watering regime, as T_0 continued to do. The T_4 pots remained on the inundation schedule until the end of the fourth week, when they too were drained and placed on the 100 ml/4 day regime. Every two days, the number of germinated seeds and seedlings in each pot was recorded. The experiment lasted six weeks - December 22 to February 2. No additional measurements were effected upon its termination since morphological differences could be attributed to variations in the time of germination, as is indicated by the mean germination dates of the survivors: T_0 - December 30, T_2 - January 1 and T_4 - January 21.

4.2.2.3. Productivity.

In order to test whether the bare areas are devoid of vegetation due to lack of seed rain and/or to environmental factors external to the tailings material itself and to compare the productivity of the S- and B tailings with the S+ tailings, the following growth experiment was designed.

Of the 120 tailings samples subjected to physical and chemical analyses, 60, two from each plot, were randomly selected:

S1 a+	S1 g+	S1 d-	S1 g-	B1 b	B1 e
S2 c+	S2 h+	S2 c-	S2 h-	B2 h	B2 e
S3 f+	S3 d+	S3 f-	S3 d-	B3 e	B3 f
S4 g+	S4 b+	S4 g-	S4 b-	B4 h	B4 d
S5 g+	S5 a+	S5 g-	S5 a-	B5 e	B5 c
S6 e+	S6 h+	S6 e-	S6 h-	B6 b	B6 d
S7 a+	S7 f+	S7 a-	S7 f-	B7 a	B7 g
S8 f+	S8 c+	S8 f-	S8 c-	B8 b	B8 h
S9 a+	S9 f+	S9 a-	S9 f-	B9 f	B9 c
S10h+	S10g+	S10h-	S10g-	B10g	B10e

Two pots per sample, 120 in total, were filled to within 2 cm of the rim with the appropriate tailings material. In one of each pair of pots, the seeds were sown on the surface; in the other at a depth of 1 cm. Given their high clay contents and physical state _in situ_ , a number of the tailings samples used in this experiment may be liable to compaction and/or surface cementation. Both surface and buried sowing was effected, as a number of researchers have found seed depth to have a differential impact upon the successful establishment of _S. pestifer_, particularly in compacted soils. Buried seeds experienced more successful establishment, a depth of about 1 cm being optimum (Evans and Young, 1972; Wallace _et al._, 1968).

For the first two weeks, each pot received 50 ml of tapwater every second day, and every third day thereafter. At each watering, the number of germinated seeds and seedlings were counted as were the visible corpses. Also noted was the condition of the latter, i.e. dehydrated/rooted, dehydrated/rooted/partially emerged or dehydrated/not rooted. The experiment was terminated on April 10, after a duration of 12 weeks. The density of many of the tailings prevented the extraction of the entire plant without damage to the roots. Consequently, only the above ground portions were considered, these being oven-dried and weighed.

4.2.2.4. Verification and Amendment.

In order to test the validity of the assumptions derived from the preceding analyses and experiments, as well as examining possible amendment procedures, the following growth experiments were executed. They are necessarily limited in scope.

A growth experiment regarding compaction and surface cementation was carried out employing 4 randomly selected samples from each of the S+, S- and B subjected to physical and chemical analyses:

S4 a+	S4 a-	B2 a
S7 g+	S4 e-	B6 g
S9 g+	S6 g-	B7 c
S10f+	S8 h-	B8 c

Three treatments were effected with each sample:

i) unmodified tailings, the control (0),

ii) 1:1 tailings:sawdust mixture (1),

iii) 1 cm sawdust layer overlying the tailings (S).

The plant pots were filled to 1 cm of the rim with the appropriate substrate. A total of 36 pots and 180 seeds, each sown at a depth of 1 cm, were utilized. Each pot received 50 ml of tapwater every second day for the initial two weeks, every third day thereafter. Concomitantly, the number of germinated seeds and seedlings was recorded. The sawdust employed was of fine consistency. It was composed primarily of pine with some fir plywood. Sawdust was selected since it has a recognized ability to improve soil compaction and cementation conditions. More importantly, in this case, is its poor nutrient status. Interference is thus unlikely. Its principal components, cellulose (approximately 40-45 %), lignin (25-30 %), hemi-cellulose (25-30 %) and extractives (0-5 %) (Gray, 1980, pers. comm.), are not readily decomposed (Hausenbuiler, 1972). Negligible decomposition and nutrient release are likely over the limited duration of the experiment. The nutrient content of the wood is poor in any case, as illustrated for two species of *Pinus* (Table 4.2).

	Pinus sylvestris (95 years old)		*Pinus excelsa* (120 years old)	
	trunk	needles	trunk	needles
N	0.11	1.29	0.09	0.84
Si	0.01	0.12	0.01	0.31
Ca	0.09	0.34	0.09	0.52
K	0.10	0.45	0.04	0.38
Mg	0.02	0.10	0.02	0.07
P	0.01	0.16	0.02	0.07
Al	0.01	0.14	0.01	0.13
Fe	T	0.01	T	0.01
Mn	0.01	0.05	0.01	0.07
S	0.01	0.11	0.01	0.03
Na	0.01	0.02	T	0.03
Total	0.38	2.79	0.30	2.46
Ratio	1:7		1:8	

Table 4.2. Percentage nutrient concentrations of the ash of *Pinus sylvestris* and *P. excelsa*. (after Rodin and Basilevic, 1967) T: trace

Peat moss also has an ameliorating effect upon soil compaction. However, its nutrient status is comparatively high, as demonstrated by Table 4.3, which provides data on the chemical properties of peat, the surface layer of which constitutes peat moss. Evans and Young (1972) observed significantly improved establishment of *S. pestifer* on compacted soils with

	Total C %	Total N %	CEC meq/ 100g	Exchangeable cations ppm Ca	K	Mg	Avail P ppm
Sphagnum cuspidatum	45.8	1.5	114	874	175	524	17
Eriophoretosum sphagnum variant	46.5	0.5	149	542	146	694	11
Ledetosum	51.7	0.7	143	2748	1224	1309	21
Sphagno-Alnetum rugosae	56.5	2.7	175	4776	284	2177	19
Thujetum occidentalis	44.7	2.2	175	17841	105	1004	6

Table 4.3. The chemical properties of peat from four associations. (after Gauthier and Grandtner, 1973)

the addition of plant litter. However, the release of nutrients would render this amendment unsuitable for this experiment. Glue is present in plywood. Biochemical interactions with the plant are unlikely, though, due to its slow rate of breakdown and its low quantity. Differential growth between the amended and control treatments may, therefore, be attributed to the alteration of the physical state, the nutrient status being held relatively constant. Not all the samples are subject to compaction or cementation. This was desirable as it provided a range over which to examine the effect of the treatments. The experiment commenced February 20 and terminated April 22, a duration of 9 weeks. As in the previous experiment, the dry weights of the surviving plants were obtained.

The available P and K concentrations of the iron tailings were found to be uniformly low. Although not measured, N is also likely to be in short supply. In a fine silty, mixed mesic soil, likely more fertile than iron tailings, Whalley and McKell (1976) observed significantly improved growth of S. pestifer with the addition of N and P. A fertilization experiment was, therefore, executed. Four samples were randomly selected from each of the S+, S- and B analysed:

S1 f+	S1 f-	B3 h
S2 g+	S7 g-	B4 c
S6 g+	S9 h-	B6 e
S8 h+	S10b-	B7 b.

Each sample received two treatments:

i) unmodified tailings, the control (0),

ii) application of NPK commercial fertilizer (N).

According to the manufacturer, the guaranteed minimum analysis of the fertilizer is:

Total nitrogen		10 %
water soluble N	none	
nitrate N	0.6%	
ammoniacal N	1.0%	
urea	8.4%	
Available phosphoric acid		15 %
unavailable P acid	none	
Soluble potash (K_2O)		10 %
Total available primary plant food		35 %.

The sources are identified as urea, ammonium and potassium phosphates and potassium nitrate. In sum, 24 pots, each filled to 1 cm of the rim, and 120 seeds were used. The pots underwent an equivalent watering schedule to those of the preceding experiment. However, one of each pair received fertilized tapwater, the other unmodified tapwater. The fertilizer concentration employed was 14 drops of liquid fertilizer per litre of tapwater. By the eighth day, it was observed that twice as many non-fertilized seeds had germinated than those receiving the NPK. As the only difference between the two treatments was the fertilizer application, it may be that this was inhibiting germination in some fashion. In experiments conducted on asbestos tailings, Moore (1980, pers. comm.) observed a similar effect, suggesting it may be due to the action of the ammonia gas produced by the volatilization of the ammonium and/or urea present in the fertilizer under alkaline conditions. Consequently, fertilization was withheld March 7-26, when germination had levelled off. During this period, all pots received tapwater. The number of germinated seeds and seedlings was regularly recorded. The experiment was carried out over a 9 week period, February 26 to April 28, whereupon the surviving plants were subjected to dry weight measurements.

The results of the field survey and of the growth experiments were subjected to analysis of variance and Chi-square, respectively, while statistical comparisons of the chemical analyses data were effected by standard score ($N > 30$), t test ($N \leq 30$) and paired observations. A significance level of 95% was used throughout. Multivariate analysis was not employed since the basic assumptions of linearity and factor independence could not be realized.

5. Results and Discussion.

5.1. Field Data.

The results of the survey of the vegetated plots are summarized in Table 5.1 and presented in full in Appendix A. In reviewing these data it must be remembered that sampling was done so as to maximize the apparent differences among these 10 plots in order to obtain adequate representation of the range of conditions present. Despite this, the between plot heterogeneity is not very pronounced. For example, there is no significant difference (p=0.05 or less) in the distance between the sampled S. pestifer individual and its nearest neighbour. While significant between plot variance was calculated for the remaining parameters, in each of these this could be attributed to the extreme values of only one or two of the ten plots.

With the elimination of S6 from the analysis of variance for the distance between S+ and S- samples, the variance between the other 9 plots is no longer significant. In the S6 plot, the vegetation was concentrated into a cluster with a few isolated individuals elsewhere in the plot, resulting in greater than average distances between the S+ and S-, particularly when the initial point fell on an S- removed from the main cluster. In fact, fully half of the distances measured were greater than the defined minimum of 25 cm, as opposed to a mean of 15 % for the other 9 plots.

In considering the number of individuals per quadrat, the between plot variance is insignificant when S2 and S5 are

Plot	Distance[1] S+ to S-	# plants per quadrat	% cover per quadrat	Distance[1] S+ to neighbour	Dry weight[2]
S1	27.5 (6.6)	1.2 (0.4)	13.3 (8.4)	16.1 (10.7)	1.7 (1.4)
S2	25.0 (0.0)	5.6 (3.0)	11.7 (12.3)	3.3 (4.3)	0.2 (0.2)
S3	30.6 (7.5)	2.1 (0.9)	8.6 (7.3)	8.2 (13.5)	0.4 (0.5)
S4	30.2 (9.1)	4.0 (4.2)	5.4 (3.0)	9.7 (5.9)	0.2 (0.1)
S5	26.0 (2.6)	8.4 (9.1)	31.2 (15.0)	3.1 (7.5)	1.6 (1.8)
S6	40.9 (17.4)	2.0 (1.0)	6.6 (3.6)	5.9 (6.3)	0.3 (0.2)
S7	25.0 (0.0)	2.6 (2.6)	11.3 (9.2)	10.4 (16.0)	0.6 (0.4)
S8	30.2 (13.2)	1.6 (0.7)	36.3 (42.2)	7.2 (10.1)	10.9 (5.4)
S9	29.2 (9.8)	3.4 (1.8)	12.5 (5.4)	3.6 (4.4)	0.5 (0.2)
S10	25.0 (0.0)	1.4 (0.5)	19.5 (18.8)	6.8 (5.4)	2.6 (4.0)
F	2.1	2.9	2.7	1.3	2.3

[1] distance in cm

[2] dry weight in g

Table 5.1. Summary of the survey of S+ plots. Values indicated are the means of 8 quadrats sampled per plot, with standard deviations in brackets. F values for p=0.05 and p=0.01 are 2.01 and 2.67, respectively.

disregarded. The high values recorded for these two plots are likely due to the presence of a few, old, i.e. previous season, S. pestifer individuals, which provided a concentrated seed supply, assuming that not all the seeds were shed in transit. This is not related to vigour, however. In the S5g quadrat, for example, the 31 plants observed were all very small. This can be contrasted with the vigourous plants in S8, each of which extended beyond the boundaries of the 25 cm^2 quadrat.

Similarly with the percentage vegetative cover, the elimination of S5 and S8 results in no significant variation between the remaining 8 plots. The comparatively dense cover of the S5 quadrats is due primarily to the presence of numerous plants. Though small in size individually, collectively they produce a dense cover. The high value obtained for S8 can be attributed to the massive size of a number of the sampled S. pestifer, 2 of which each provided 100 % cover.

In comparing the dry weights of the S. pestifer specimens collected, the between plot variance is nullified with the elimination from consideration of S8 and S10, which together have the 4 plants of greatest mass, 3 in the former, 1 in the latter, as is indicated by the high mean dry weight values.

It is suggested, therefore, that, with minor exception, the distribution dynamics of S. pestifer on the tailings strip are relatively homogeneous. The anomalous cluster of exceptionally vigourous individuals on the S8 plot accounts for much of the observed variation, as does the presence of previous season

S. pestifer plants, particularly on S5.

No consistent pattern was discerned in relation to microtopography and resultant microclimate (shade, wind exposure, insolation, temperature, etc.), with S+, S- and B occurring irrespective of slope angle, aspect or the presence of depressions of various dimensions (troughs, microbasins, etc.). There were no objects other than the plants themselves to cast shade and this would be limited given their annual habit and the small size of the majority of the S. pestifer individuals on the tailings strip. As previously stated, four plots (B4, B7, B8 and B10), each devoid of vegetation, were observed to be subject to seasonal inundation by the tailings pond (see 5.2.2.2.).

5.2. Laboratory Data.

5.2.1. Physical and Chemical Analyses.

The results of the physical and chemical analyses of the tailings material are summarized in Table 5.2 and presented in their entirety in Appendix B.

The colour of the tailings surface did not vary appreciably within or between plots, ranging between 5Y5/1 (gray) and 5Y5/2 (olive gray) under moist conditions and rising on average a single value unit on drying. The B2 plot was an exception. Not only was the overall colour darker, 2.5YR3/0 (very dark gray) when moist, but also numerous reddish particles were apparent. These may reflect the presence of oxidized iron (Fe^{3+}), which is particularly insoluble, precipitating at pH

Sample	Compac-tion	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)* Ca	Mg	K	Na	H	C.E.C. meq/100g
S1+	x	sand	8.0	0.44	10.62	1.14	0.08	0.09	0.0	11.94
S1-	x	sand	8.1	0.22	11.94	0.80	0.09	0.03	0.0	12.86
B1	x	sand	8.1	T	12.12	0.73	0.11	0.03	0.0	12.99
S2+	x	sand	8.0	T	12.69	0.62	0.10	0.03	0.0	13.44
S2-	x	sand	7.8	0.22	14.25	0.77	0.11	0.04	0.0	15.17
B2	x	sand	6.9	T	10.56	1.67	0.08	0.04	0.0	12.35
S3+	✓	clay	8.0	T	18.94	2.39	0.30	0.03	0.0	21.66
S3-	✓	clay	7.9	T	18.69	2.13	0.26	0.10	0.0	21.13
B3	✓	clay	8.1	T	18.81	3.85	0.34	0.10	0.0	23.11
S4+	✓	clay	8.1	T	18.31	3.85	0.40	0.12	0.0	22.68
S4-	✓	clay	8.2	T	19.81	4.58	0.38	0.27	0.0	25.05
B4	✓	clay	8.2	T	23.50	7.71	0.70	0.39	0.0	32.30
S5+	✓	clay	7.9	0.44	17.25	4.48	0.54	0.49	0.0	22.75
S5-	✓	clay	8.0	T	20.06	6.02	0.59	0.79	0.0	27.47
B5	✓	clay	8.1	0.22	19.44	3.85	0.45	0.25	0.0	23.99
S6+	✓	clay	8.1	0.22	20.44	3.23	0.35	0.23	0.0	24.25
S6-	✓	clay	8.2	T	22.06	2.54	0.48	0.39	0.0	25.47
B6	✓	clay	8.2	T	34.50	10.42	1.03	0.48	0.0	46.42
S7+	x	silt	8.3	0.87	14.12	2.19	0.20	0.05	0.0	16.56
S7-	x	silt	8.2	1.31	15.87	1.78	0.28	0.15	0.0	18.08
B7	x	silt	8.5	T	13.94	2.19	0.35	1.15	0.0	17.63

* with NH_4OAc (pH 7.0)

Sample	Compaction	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)*					C.E.C. meq/100g
					Ca	Mg	K	Na	H	
S8+	x	silt	8.1	0.44	14.44	1.35	0.17	0.03	0.0	16.00
S8-	x	silt	8.1	T	17.19	1.15	0.25	0.11	0.0	18.69
B8	x	silt	8.4	T	17.37	3.54	0.38	0.51	0.0	21.81
S9+	✓	clay	8.1	T	16.31	3.02	0.32	0.19	0.0	19.85
S9-	✓	clay	8.1	T	21.83	3.22	0.38	0.23	0.0	25.67
B9	✓	clay	8.3	T	27.75	5.83	0.37	0.28	0.0	34.24
S10+	x	sand	8.0	T	13.62	0.73	0.10	0.03	0.0	14.48
S10-	x	sand	7.9	T	14.94	0.86	0.11	0.04	0.0	15.95
B10	x	sand	7.9	T	12.81	1.87	0.15	0.10	0.0	14.95

* with NH_4OAc (pH 7.0)

Table 5.2. Summary of the physical and chemical analyses of the tailings material. Values indicated are the means of 4 samples per plot. x: not compacted; ✓: compacted; T: trace

values higher than 3.0 (Buckman and Brady, 1969). It is unlikely that differential albedo is influential except perhaps on the B2 plot where the heightened diurnal heat flux and the increased absorption of solar radiation, with its resultant surficial heating, may be detrimental to the species or more specifically to the local ecotype.

A cursory examination of the compaction data presented in Table 5.2 and Appendix B would suggest the elimination of this parameter from consideration as a possible limiting factor, there being greater homogeneity within each set of S+, S- and B (eg. S1+, S1- and B1) than within the overall S+, S- or B groupings. This is not substantiated, however, by the results of the related growth experiments (see 5.2.2.).

With the exception of B2, which was very slightly acidic, the pH values were consistently alkaline, slightly to moderately so, with a range of 7.8 to 8.5. Given the non-sulphide nature of the tailings, it can be expected that the pH will remain relatively constant over time unless artificially modified. This can be realized through such procedures as the mixing of acid organic matter, eg. leafmould, pine needles, tanbark or peatmoss, with the tailings or by the application of ferrous sulphate or flowers of sulphur (Buckman and Brady, 1969). As to be expected given the observed alkalinity, the available P of the tailings was consistently very low, according to the classification of Olsen and Dean (1965):

<3 ppm	very low	7-20 ppm	medium
3-7 ppm	low	>20 ppm	high.

No significant variation between S+, S- or B samples was found.

The unmeasurably low quantity of available P in the B2 samples, particularly B2a (pH 6.5) and B2h (pH 6.3), which possess pH values amenable to P solubility, would suggest that there exist very low concentrations of P in the tailings and that a reduction in pH would not augment its availability. The mineralogy of the tailings, as defined by Collings (1977), would support this. However, excessive Ca, which is known to interfere with P nutrition, may also be operative. Exchangeable K was also observed to be low, with mean concentrations of 0.26, 0.29 and 0.40 meq/100 g for the S+, S- and B categories, respectively. This could be attributed to low supply and/or to the domination of the exchange complex by Ca, which may depress the availability of the associated cations. Given the presence of muscovite (10-20 %), biotite (10-20 %) and orthoclase (< 10 %) in the tailings (Collings, 1977), the latter would be indicated. If it can be assumed that N is also lacking, we have agreement with the findings of other researchers that mine tailings are frequently deficient in N, P and K. This is dramatically illustrated by the results of the NPK experiment (see 5.2.2.5.).

Na concentrations were very low. This may reflect both an availability depressed by the domination of the exchange complex by Ca and poor supply, since albite, its likely source, is only a minor mineral component. While S. pestifer is said to be a halophyte, it may be that it can perform vigourously under non-saline conditions (actual or effective). Though all the samples displayed low exchangeable Na concentrations, the B had significantly higher values than did S+ or S- (0.33 meq/

100 g as opposed to 0.13 and 0.21 respectively). A similar relationship was observed with K. This can be explained by proximity to vegetation and the resultant density of living plant roots in the sample in situ. The highest density of roots and thus the greatest nutrient extraction occurs in the S+ samples. Nutrient absorption from S- samples is confined to the action of peripheral roots, while the nutrient store of the B samples is virtually untapped. Sampling was effected prior to nutrient replenishment via plant decomposition, largely roots and leaves, which are shed prior to flowering.

Table 5.3 compares the exchangeable Ca and Mg concentrations obtained using NH_4OAc and NaOAc as extractants. Although the Ca concentrations were lower with the latter, as expected, the Ca:Mg ratios remained consistently greater than 1.0. Consequently, it is unlikely that Mg toxicity is a limiting factor despite the CANMET measurements (Collings, 1977). In fact, on examining the Ca:Mg ratios obtained with NaOAc, the majority lie within the optimum range of 1.0-5.0. There is no significant difference in Ca:Mg ratios according to S+, S- or B. While B4 and B6 displayed high mean Ca concentrations, the associated Mg values were similarly elevated, producing desirable Ca:Mg ratios. Despite its reduction with the NaOAc, exchangeable Ca continued to dominate the exchange complex.

To facilitate their examination, the CEC data are summarized (using mean values) as follows:

	sand	silt	clay	overall
S+	13.25	16.28	22.73	18.36
S-	14.51	18.39	25.61	20.56
B	13.43	19.22	31.12	23.98

Sample	Ca NH_4	Ca Na	Mg NH_4	Mg Na	Ca:Mg NH_4	Ca:Mg Na	Ca:Mg NH_4:Na
S1g+	10.75	3.00	0.83	0.54	12.95	5.55	2.33
S1g-	10.75	3.00	0.83	0.67	12.95	4.48	2.89
B1e	12.50	3.25	0.42	0.46	29.76	7.06	4.21
S2g+	13.25	3.50	0.42	0.71	31.55	4.93	6.40
S2g-	13.25	2.75	0.83	0.50	15.96	5.50	2.90
B2h	9.75	7.00	2.50	1.92	3.90	3.65	1.07
S3a+	18.75	8.00	2.08	1.58	9.01	5.06	1.78
S3a-	18.50	8.00	1.67	1.83	11.08	4.37	2.53
B3f	15.25	5.00	2.92	3.00	5.22	1.67	3.13
S4g+	17.25	9.00	4.58	5.50	3.77	1.64	2.30
S4g-	20.00	5.00	8.33	3.33	2.40	1.50	1.60
B4e	28.50	25.00	10.00	7.92	2.85	3.16	0.90
S5b+	17.50	7.50	5.83	3.75	3.00	2.00	1.50
S5b-	26.50	10.00	11.67	6.25	2.27	1.60	1.42
B5e	16.25	8.00	3.33	3.50	4.88	2.29	2.13
S6a+	11.75	3.00	0.83	0.58	14.16	5.17	2.74
S6a-	11.75	3.00	0.83	0.54	14.16	5.55	2.55
B6b	39.00	37.50	13.33	15.42	2.93	2.43	1.21
S7f+	14.00	3.75	5.00	3.33	2.80	1.13	2.48
S7f-	14.75	5.00	4.58	3.67	3.22	1.36	2.37
B7b	13.50	3.50	2.50	2.58	5.40	1.36	3.97
S8g+	17.00	6.00	1.67	0.92	10.18	6.52	1.56
S8g-	17.25	6.50	1.25	0.92	13.80	7.06	1.95
B8a	18.00	9.00	4.17	5.67	4.32	1.59	2.72

Sample	Ca NH$_4$	Ca Na	Mg NH$_4$	Mg Na	Ca:Mg NH$_4$	Ca:Mg Na	Ca:Mg NH$_4$:Na
S9a+	15.25	6.00	2.92	2.50	5.22	2.40	2.17
S9a-	26.50	5.00	3.75	2.08	7.07	2.40	2.95
B9d	32.00	6.25	5.42	2.50	5.90	2.50	2.36
S10f+	16.50	4.00	0.83	0.92	19.88	4.35	4.57
S10f-	14.00	4.25	0.83	0.87	16.87	4.88	3.46
B10f	6.50	7.50	2.08	1.33	3.12	5.64	0.55

Table 5.3. A comparison of the Ca and Mg concentrations and ratios obtained with NH$_4$OAc and NaOAc.

Due to the paucity of organic matter, particularly humus, the CEC likely originates from isomorphous substitution and broken bonds within the mineral fraction. Consequently, it is apt to be relatively stable. As would be expected, the CEC values increase with diminishing particle size. While these differences are statistically significant, all samples had CEC values suitable for plant growth. In fact, the lowest were obtained from S+ material. As such, it is unlikely that CEC is limiting.

5.2.2. Growth Experiments.

5.2.2.1. Germinability Experiment.

The results of the germinability experiment are presented in Table 5.4. Although Wallace *et al.* (1968) and Dwyer and Wolde-Yohannis (1972), in separate experiments, had observed germination within a half hour following the addition of water, in the present study initial germination was recorded only after 24 hours, and this for only 2 of the 250 seeds employed (0.8 %). Substantial germination occurred only by the end of the first week (75.6 %), a significant increase from the preceding observation of 20.4 % after 4 days. Ecotypic variation may account for the discrepancy with the literature. The seeds employed by Wallace *et al.* and Dwyer and Wolde-Yohannis were obtained from plants growing in the semi-arid American southwest, in California and New Mexico, respectively. The ability to germinate rapidly upon exposure to moisture would be selectively advantageous in such areas of limited precipitation, a non-essential adaptation in the temperate climate of southwestern Québec, where temperature, rather than moisture, is more

Plot	Dec 5	Dec 6	Dec 9	Dec 12	Dec 15	Dec 18	Dec 21
S1	0 (0)	0 (0)	2 (8)	12 (48)	21 (84)	21 (84)	21 (84)
S2	0 (0)	0 (0)	7 (28)	24 (96)	24 (96)	24 (96)	24 (96)
S3	0 (0)	0 (0)	7 (28)	19 (76)	21 (84)	21 (84)	21 (84)
S4	0 (0)	2 (8)	9 (36)	22 (88)	24 (96)	24 (96)	24 (96)
S5	0 (0)	0 (0)	4 (16)	19 (76)	22 (88)	22 (88)	22 (88)
S6	0 (0)	0 (0)	9 (36)	18 (72)	19 (76)	19 (76)	19 (76)
S7	0 (0)	0 (0)	2 (8)	21 (84)	23 (92)	23 (92)	23 (92)
S8	0 (0)	0 (0)	0 (0)	17 (68)	17 (68)	17 (68)	17 (68)
S9	0 (0)	0 (0)	6 (24)	16 (64)	17 (68)	17 (68)	17 (68)
S10	0 (0)	0 (0)	5 (20)	21 (84)	23 (92)	23 (92)	23 (92)
Total	0	2	51	189	211	211	211
	(0)	(0.8)	(20.4)	(75.6)	(84.4)	(84.4)	(84.4)

Table 5.4. Seedling count and rate of germination (%) in the germinability experiment.

often limiting. The peak germination rates were sufficiently high (68-96 % per plot and 84.4 % overall), however, to warrant the immediate use of the seeds in the growth experiments. Pretreatment, such as stratification, was not indicated. This was also found by Young and Evans (1972). It is interesting to note the comparatively poor performance of the S8 seeds, derived from vigourous plants <u>in situ</u>. The response, though, was remarkably homogeneous. Consequently, it was decided to employ S8 seeds exclusively, despite their poor germination rate, in order to better control seed variability. (The results of subsequent growth experiments justified this, since a number of samples experienced 100 % germination.)

5.2.2.2. <u>Inundation Experiment</u>.

Wetting is required for the germination of <u>S. pestifer</u>, whether through new cell division or, as Wallace <u>et al.</u> (1968) suggest, through cell elongation upon the absorption of water. However, as the results of the inundation experiment (Fig. 5.1.a) indicate, prolonged inundation is detrimental to the species. This did not become evident until after the second week, prior to which there was no significant difference (p= 0.05 or less) between the three inundation treatments. Two distinct causes of mortality were observed according to the length of time inundated prior to drainage: dehydration and rotting. Although the seedlings of the T2 (2 weeks inundation) group were vigourous at the time drainage was implemented, many very shortly succumbed to dehydration. The seedlings of the T4

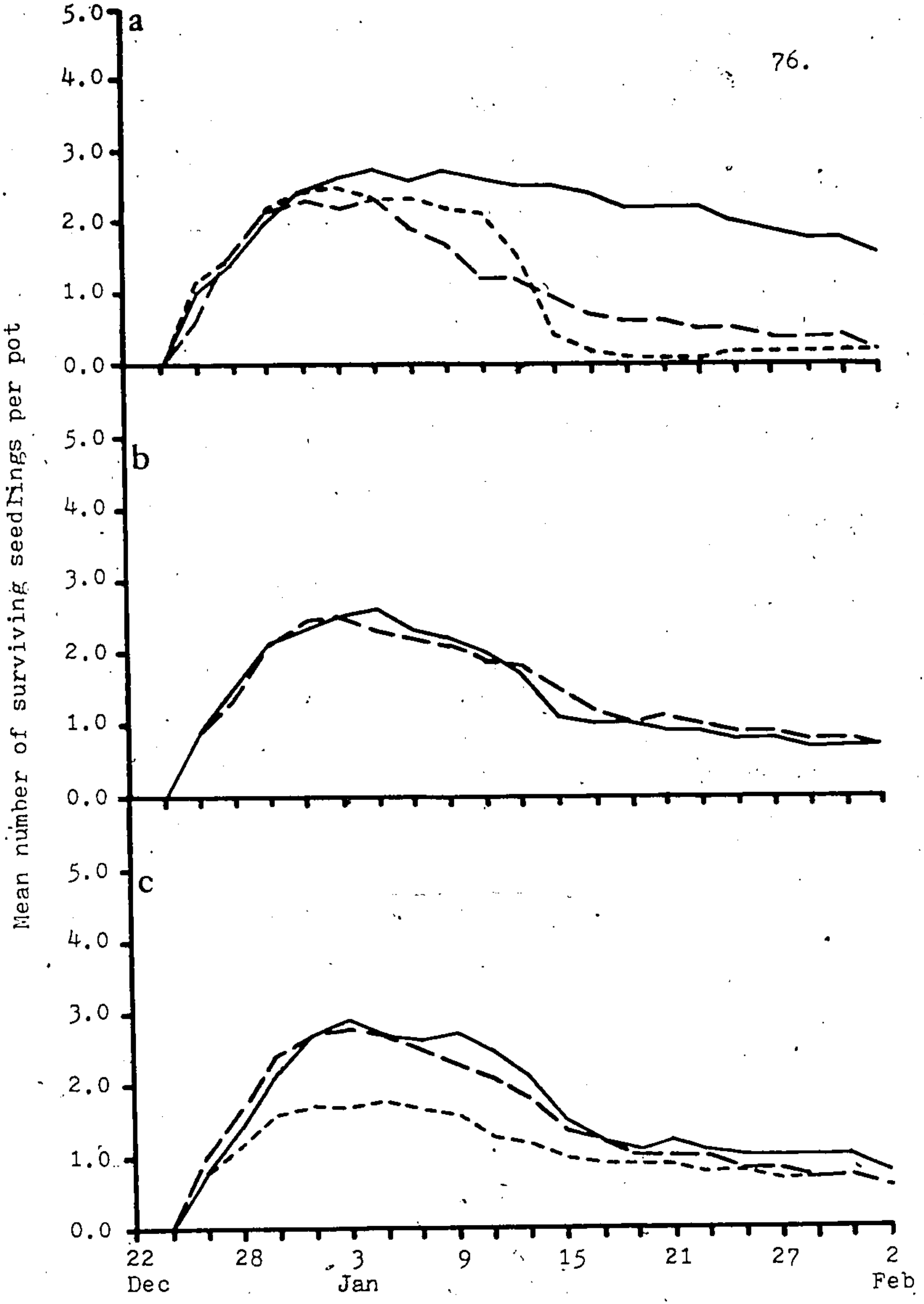


Fig. 5.1. Comparison of the mean survival for each a) period of inundation, b) substrate and c) depth of sowing. a) ——— : T0; — — — : T2; - - - - : T4; b) ——— : sand; — — — : vermiculite; c) ——— : surface; — — — : 1 cm; - - - - : 2½ cm.

(4 weeks inundation) group rotted despite the addition of fresh water every second day, which was thought sufficient to prevent anaerobic conditions. Their numbers declined drastically over a period of 4 days during the fourth week. A few seeds germinated after drainage was provided.

While there was no significant difference in the overall performance of S. pestifer according to substrate (Fig. 5.1.b), this in fact masks the differences that present themselves upon subdivision into inundation treatment groups (Fig. 5.2). The control T0 (no inundation) plants were more successful on sand than on vermiculite. The latter may have been too moist for the supposedly drought-tolerant species. In contrast, for the T2 group mortality was experienced earlier and to a greater degree on sand. Since vermiculite has a superior moisture retention capacity, the seedlings may not have dehydrated to such an extent or as quickly as those on sand. This does not contradict the previous statement. All the T0 seedlings were rooted, whereas most of the T2 seedlings lay entirely on the surface and were thus subject to greater atmospheric drying. Among the T4 plants there was greater germination on sand, however, the numbers plummeted during the fourth week. The rotting of the seedlings may have been exacerbated by the development of a fungus to which the sand was particularly prone.

The overall performance in relation to the depth of sowing (Fig. 5.1.c) also requires more detailed scrutiny (Fig. 5.3). The pattern of low germination and emergence at 2½ cm

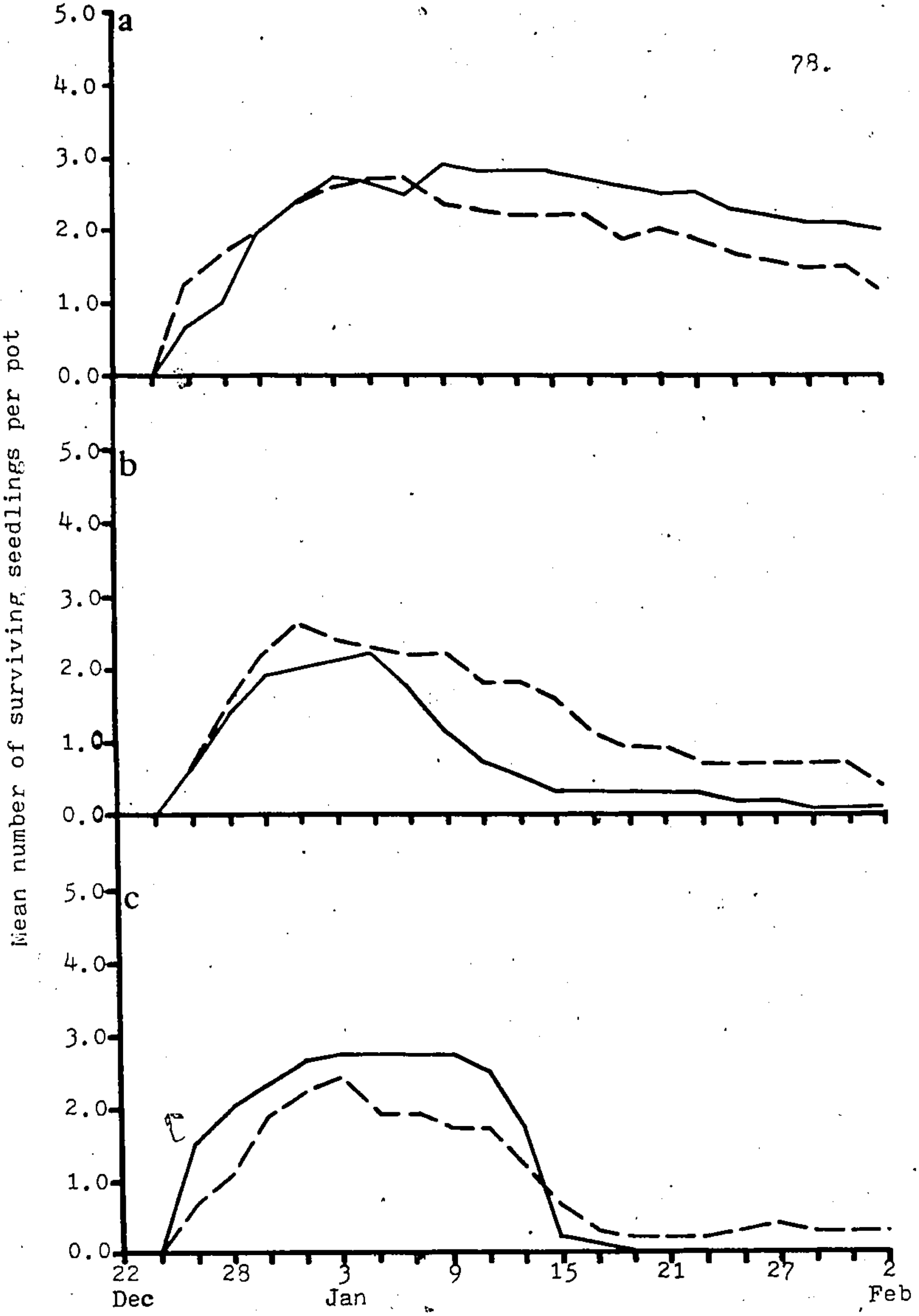


Fig. 5.2. Comparison of the mean survival for each substrate under the a) T0, b) T2 and c) T4 inundation treatments. ——— : sand; — — :vermiculite.

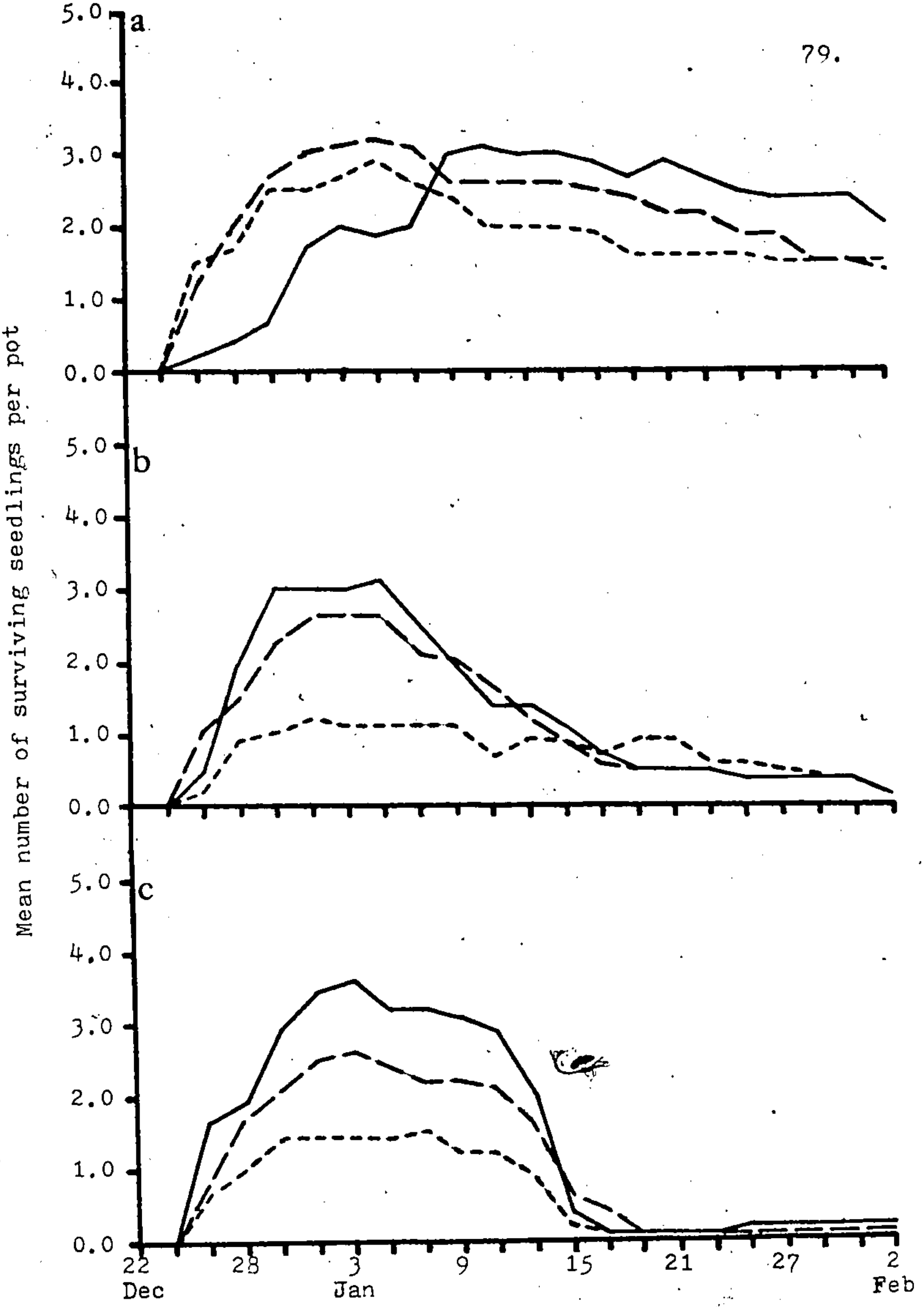


Fig. 5.3. Comparison of the mean survival for each depth of sowing under the a) T0, b) T2 and c) T4 inundation treatments. ——— :surface; — — :1 cm; - - - - :2½ cm.

remained in both T2 and T4. Compaction of the substrate due to the weight of the overlying water and saturated substrate may have inhibited germination and emergence via mechanical impedance. However, a lower relative mortality was observed for the T2 plants sown at 2½ cm as compared with those at the surface and 1 cm. It is suggested that due to the buoyancy of the water, the surface and to a lesser degree the 1 cm seedlings were unable to adequately anchor themselves into the substrate while uncoiling. By the time the pots were drained the seedlings had completely uncoiled and were thus unable to exert the force required for anchorage, the removal of the water notwithstanding. Sowing at a depth of 2½ cm may have provided adequate anchorage despite inundation and resultant reduction in susceptibility to dehydration upon drainage. The T4 plants also exhibit lower relative mortality with increased depth of sowing. However, given the simultaneous sharp decline at the three depths, one may expect extreme mortality irrespective of sowing depth. The pattern of the T0 group differed from the foregoing, with greater initial germination and emergence at 1 and 2½ cm rather than at the surface. This may be due to the higher moisture level below the substrate surface, which facilitated germination.

Inundation _in situ_ may have additional ill-effects, which the present experiment did not unveil. For example, seeds and/or seedlings may be removed through flotation or the chemical composition of the pond water may be antagonistic to _S. pestifer_.

5.2.2.3. Productivity Experiment.

While inundation has been shown to be detrimental to S. pestifer, an examination of the productivity experiment data suggests that in addition to inundation there exist other limiting factor(s) in the B4, B7, B8 and B10 plots (Table 5.5). Were inundation the sole factor limiting the in situ establishment of S. pestifer on the four plots, it would be expected that the performance of the species on them in the productivity experiment, in which no sample was inundated, would approximate that on the S+ material. Except for B8(0), the former is consistently inferior to the S+, both in the number of survivors and their dry weights. The B4 samples are subject to compaction. However, survival on them was poorer than on the S+ compacted samples throughout the duration of the experiment and irrespective of the sowing depth. In fact, on B4(1) no emergence was observed at any time. The data obtained from the physical and chemical analyses of the tailings provide no apparent explanation for this or for the inferior performance of the B7(0,1), B8(1) and B10(0,1) samples. However, as the experiment was conducted in a growth chamber with a relatively homogeneous environment and frequent rerandomization of the plant pots, the unidentified limiting factor(s) can be expected to occur in the tailings material itself. For example, a deleterious ionic balance derived from residues of the pond water may be in effect. While the data exclude Ca, Mg, K and Na, salts not subjected to quantification may be involved,

	3 weeks	6 weeks	9 weeks	12 weeks	Dry weight
B2(0) x	3.0	1.0	0	0	0
B2(1) x	4.0	3.0	1.5	1.5	11.0
B4(0) ✓	2.5	2.0	0	0	0
B4(1) ✓	0	0	0	0	0
B7(0) x	4.0	3.0	2.0	1.0	5.1
B7(1) x	3.5	2.5	2.0	2.0	14.9
B8(0) x	4.5	4.0	3.0	2.5	13.2
B8(1) x	3.0	2.5	1.0	0.5	0.8
B10(0)x	4.0	1.0	0.5	0	0
B10(1)x	3.5	2.5	1.5	1.5	4.5
S+(0) x	4.3	2.8	2.5	1.6	15.3
S+(1) x	3.5	3.1	2.7	2.5	22.3
S+(0) ✓	3.7	2.7	2.3	1.8	18.4
S+(1) ✓	3.1	1.9	1.8	1.7	11.4

Table 5.5. A comparison of the mean number of survivors and mean dry weights (mg) in the productivity experiment for the B2, B4, B7, B8, B10 and S+ samples. Numbers in brackets indicate the depth of sowing in cm; x: uncompacted; ✓: compacted.

such as nitrate or sulphate. The anomalous B8(0) results may simply be stochastic, eg. a fortuitous selection of vigourous seeds. A particularly benign growth milieu is unlikely since B8(0) and B8(1) consisted of the same well-mixed tailings material, differing only in the depth of sowing. It is recognized that surface and subsurface environments differ in such characteristics as relative humidity, temperature and insolation, even over as little a distance as 1 cm. However, on the other uncompacted tailings in the experiment the ultimate survival of the buried (1) was consistently better than their surface (0) counterparts.

In a similar comparison, the performance, both in the number of survivors and their dry weights, on the very dark gray B2 samples was observed to be significantly inferior to that on the more lightly coloured S+ tailings material, irrespective of the sowing depth (Table 5.5). This may have been due to differential albedo. The rapid decline and ultimate failure of the B2 surface sown seedlings, on which the effects would be more pronounced, would support this supposition. However, as verification was not attempted, a definitive statement cannot be provided.

The results of the productivity experiment, when subdivided according to compaction, provide information on the effect of seed burial in relation to compaction (Table 5.6).

	3 weeks		6 weeks		9 weeks		12 weeks		Dry weight	
	x	✓	x	✓	x	✓	x	✓	x	✓
S+(0)	4.3	3.7	2.8	2.7	2.5	2.3	1.6	1.8	15.3	18.4
S+(1)	3.5	3.1	3.1	1.9	2.7	1.8	2.5	1.7	22.3	11.4
S-(0)	4.4	4.1	3.1	3.3	2.7	3.1	2.0	2.6	16.7	23.2
S-(1)	3.2	3.2	3.1	2.9	2.7	2.8	2.4	2.3	25.9	19.0
B(0)	4.0	2.4	2.4	2.8	1.5	1.8	1.1	1.1	9.4	9.3
B(1)	3.7	1.4	2.9	1.0	1.9	1.0	1.3	1.0	6.7	5.5

Table 5.6. Mean number of survivors and mean dry weight (mg) on uncompacted (x) and compacted (✓) tailings during the productivity experiment. Numbers in brackets indicate the depth of sowing in cm.

At its termination four relevant relationships were discerned:

i. on uncompacted tailings, buried was superior to surface;
ii. on compacted tailings, surface was superior to buried;
iii. of the surface sown seeds, compacted was superior to uncompacted;
iv. of the buried seeds, uncompacted was superior to compacted.

The peak germination/emergence was higher for the uncompacted tailings than for the compacted, irrespective of seed depth, the discrepancy being most marked for B(0) and B(1). As well, within each pair of samples the unburied seeds germinated and emerged more successfully than those at a depth of 1 cm. However, over the duration of the experiment, the "surface" seedlings of the uncompacted tailings were subject to greater mortality, through desiccation, than were those from buried seeds. Being uncompacted, infiltration was not significantly impeded, consequently the surficial layer was apt to dry out between waterings, this effect declining with depth. At the commencement of the experiment, when water was applied every two days, desiccation was not observed and germination, therefore, not likely impaired. Thus, due to its lesser mortality, the "buried" seedlings ultimately fared better on the uncompacted tailings than their "surface" counterparts, despite their lower peak germination/emergence. On the compacted tailings, however, mortality was greater for the buried seedlings due to the difficulty of emerging through to the surface. Many seedlings were observed to have died only partly emerged. The discrepancy was heightened by their lower peak performance. Due to the poor infiltration capacity of the compacted tailings, the surface would retain most of the water applied until it had evaporated. It is probable that inadequate aeration as well as mechanical impedance are operative in the compacted material. Capillarity was likely not a factor since the pots had drainage provided at their base. The enhanced moisture concentration at the surface of the compacted samples may account for the third observation. It should be noted that the compacted tailings became so only about a week into the experiment. A considerable proportion of the total germination/emergence on the S+ and S- compacted tailings had occurred prior to this (Table 5.7). Having become established prior to the compaction of the substrate in which they grew, these individuals may not have been as subject to the ill-effects of compaction as those becoming established afterwards.

	Uncompacted	Compacted
S+(0)	35	51
S+(1)	37	55
S-(0)	47	65
S-(1)	27	56
B(0)	22	22
B(1)	17	48

Table 5.7. Percentage of the total germination/emergence having occurred by day 6 of the productivity experiment.

The data suggest that in situ the S. pestifer individuals observed on compacted tailings may have:

i. been derived from seeds lodged on the surface of the tailings;

ii. become established prior to compaction.

The first is likely only in microdepressions where rainwater would accumulate and exposure to the evaporation effect of the wind would be minimal. On the compacted tailings in situ several S. pestifer individuals were located in advantageous micro-terrain, including troughs of varying dimensions, cracks and microbasins. While troughs were also observed in bare plots, other factors may have restricted S. pestifer ecesis.

The results of the productivity experiment demonstrate the consistently poorer performance of the B samples in comparison to that of the S+ and S-. While it is generally recognized that growth under laboratory conditions is often reduced to a degree in comparison to that in situ, this would affect the S+ and S- as well as the B samples. Both the number of survivors (Fig. 5.4) and their dry weights (Table 5.8) are inferior. While peak germination/emergence for the B(1) (buried

	Surface	Buried
S+	16.6	17.5
S-	19.7	23.0
B	9.4	6.1

Table 5.8. Mean dry weights (mg) of the productivity experiment survivors.

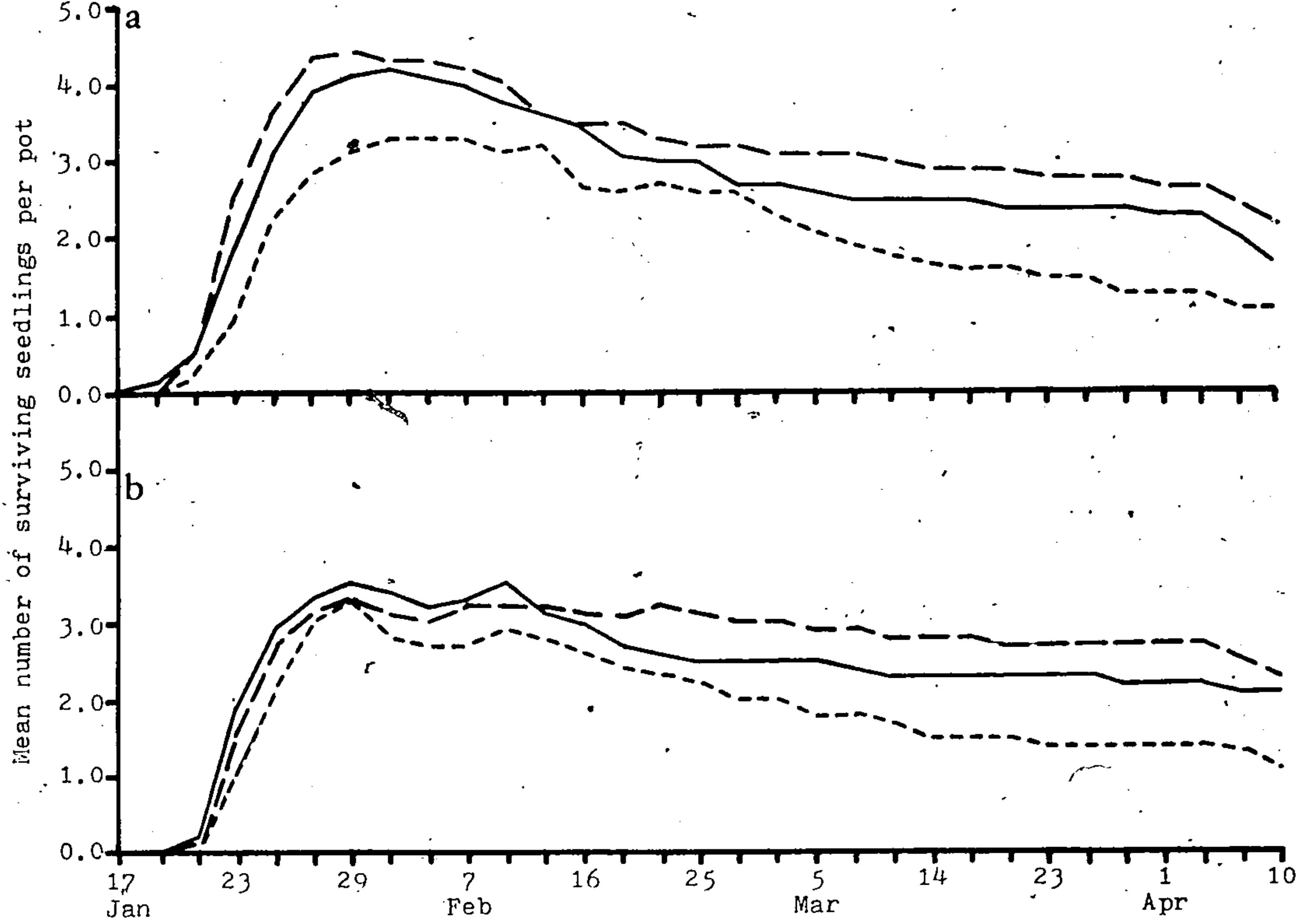


Fig. 5.4. Comparison of the mean surv,ival on the S+, S- and B tailings, a) surface and b) buried, in the productivity experiment. ——— ;S+; — — ;S-; - - - - ;B.

seeds) samples was only slightly lower than that of S+ and S-, survival was poor and vigour meagre. Antagonistic environmental properties rather than the absence of seed is the suggested explanation for the absence of *S. pestifer* on the B plots *in situ*. The data further indicate that the limiting factor(s) are within the tailings material itself.

5.2.2.4. Sawdust Experiment.

In the sawdust experiment there was a significant difference in the numbers (Fig. 5.5) and dry weights (Table 5.9) of the surviving plants on uncompacted and compacted tailings in the control set. An important anomaly was observed, however. In the B8c compacted sample, 3 of the 4 survivors were located in large cracks, which closed only after the plants were well-established, with no apparent detrimental effect on the plants. Thus, the compacted B mean survival was higher than expected. It was, in fact, superior to the

	Control	1:1 mix	Sawdust layer
S+ x	25.0	0.9	4.4
S+ ✓	3.8	0	5.3
S- x	24.6	2.1	1.4
S- ✓	1.4	0	3.4
B x	5.7	2.8	3.2
B ✓*	8.8	0.5	5.1
B ✓	0		

Table 5.9. Mean dry weights (mg) of the sawdust experiment survivors.
*without B8c

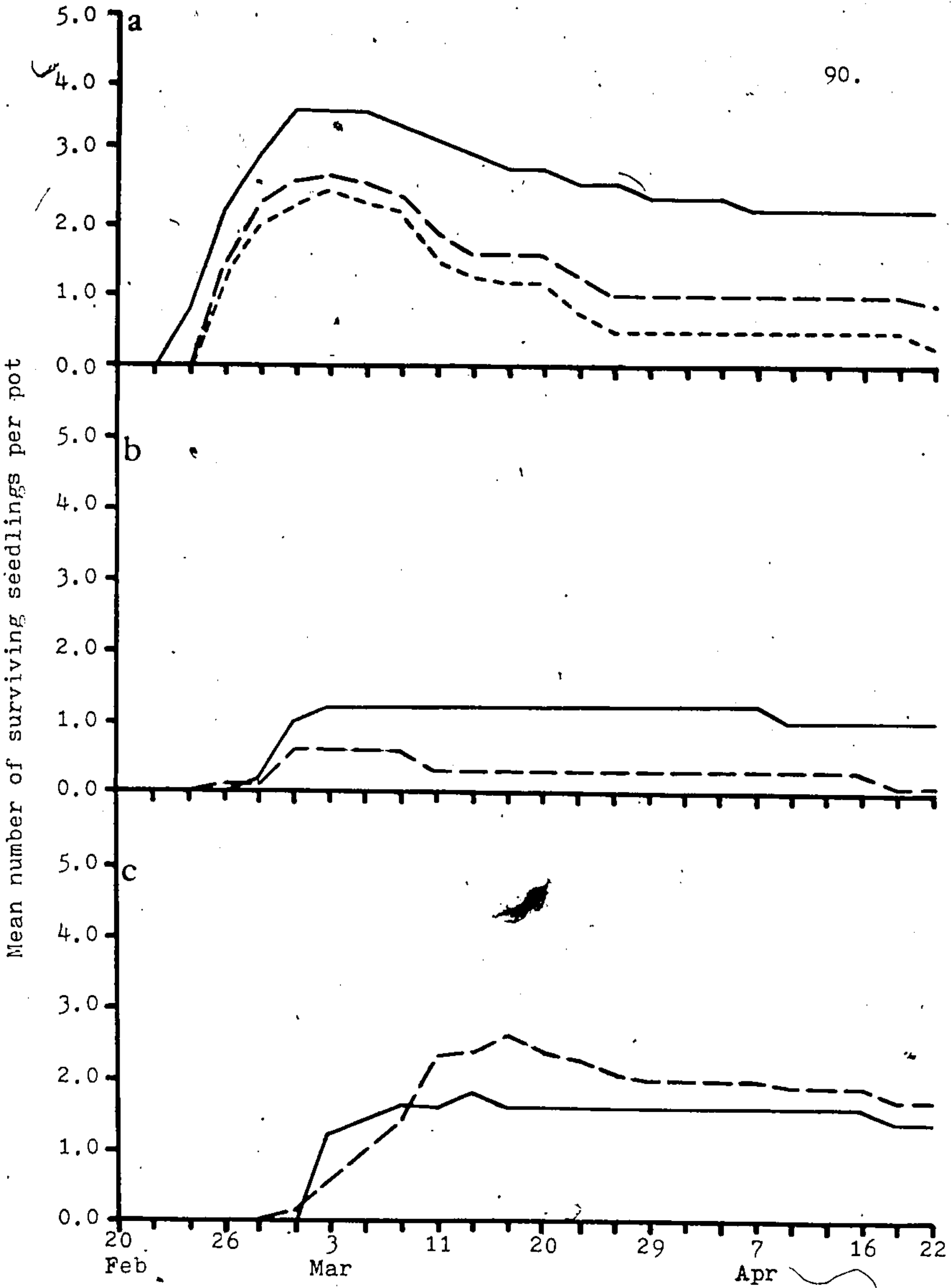


Fig. 5.5. Comparison of the mean survival on uncompacted and compacted tailings under the a) control, b) 1:1 mix, and c) 1 cm sawdust treatments. ——— :uncompacted; — — — :compacted; - - - - :compacted without B8c.

compacted S+ and S- samples and superior, as well, to the uncompacted B samples. It did not approximate the performance on the uncompacted S+ and S- samples, however. Nevertheless, this may account for the presence of S. pestifer on compacted plots in situ, i.e. fortuitous location in cracks which may or may not have closed after emergence. With the elimination of the uncharacteristic B8c sample from the examination, a consistent pattern was obtained. As would be expected on the control set, performance was significantly better on the uncompacted samples, with the S+ and S- being comparably vigourous and the B significantly less so. The 1 cm sawdust layer treatment reversed this trend, the number of survivors and their dry weights being superior on the compacted samples than on their uncompacted counterparts. Their performance was also superior to that on the compacted tailings subject to the control or 1:1 mix treatments. However, conditions were not sufficiently improved for their performance to approximate that of the uncompacted control tailings. The observed germination/emergence was considerably depressed on the uncompacted sawdust layer tailings in comparison to the control counterpart. It may be that germination itself was not affected, but rather that the seedlings rotted prior to emergence. This is suggested by two observations. Firstly, the few seedlings that did die after emergence succumbed to rotting, whereas desiccation was the apparent cause of death on the control samples. Secondly, the sawdust layer did not completely dry out between waterings. The 1:1 volume mix treatment did not significantly reduce compaction. Consequently, performance was superior on the uncompacted 1:1 mix samples, though significantly inferior to that on the control tailings. Oddly, of the uncompacted 1:1 mix tailings, the B samples were the most successful, followed by S-, with the S+ least so. This anomaly defies rational explanation.

While field experimentation is required for confirmation, it would seem that the more readily employed sawdust layer treatment is more successful than the sawdust:tailings mix in alleviating the effects of the compaction/cementation of the tailings and promoting S. pestifer establishment. However, the marginal improvement afforded by the former renders its use questionable on a cost:benefit basis. Other treatments may be more suitable. In his test plot study, Blakeman (1976) employed mulches consisting of oat straw, rotten sawdust and crushed rock, applied individually or in combinations. The latter increased the effectiveness of the organic mulches, but inhibited the emergence of some seedlings. S. pestifer individuals were significantly more developed when in mulched beds.

5.2.2.5. NPK Experiment.

It is interesting to note the difference in the number of seedlings observed for each treatment (Fig. 5.6). The peak germination/emergence was significantly higher on the control samples. However, the seedlings experienced considerably greater mortality than did the fewer, but more vigourous, fertilized seedlings. As suggested in the description of methodology, the depressed germination/emergence of the NPK group may have resulted from the inhibitory effect of ammonia gas. Despite the substitution of tapwater over a 3 week period, germination/emergence did not

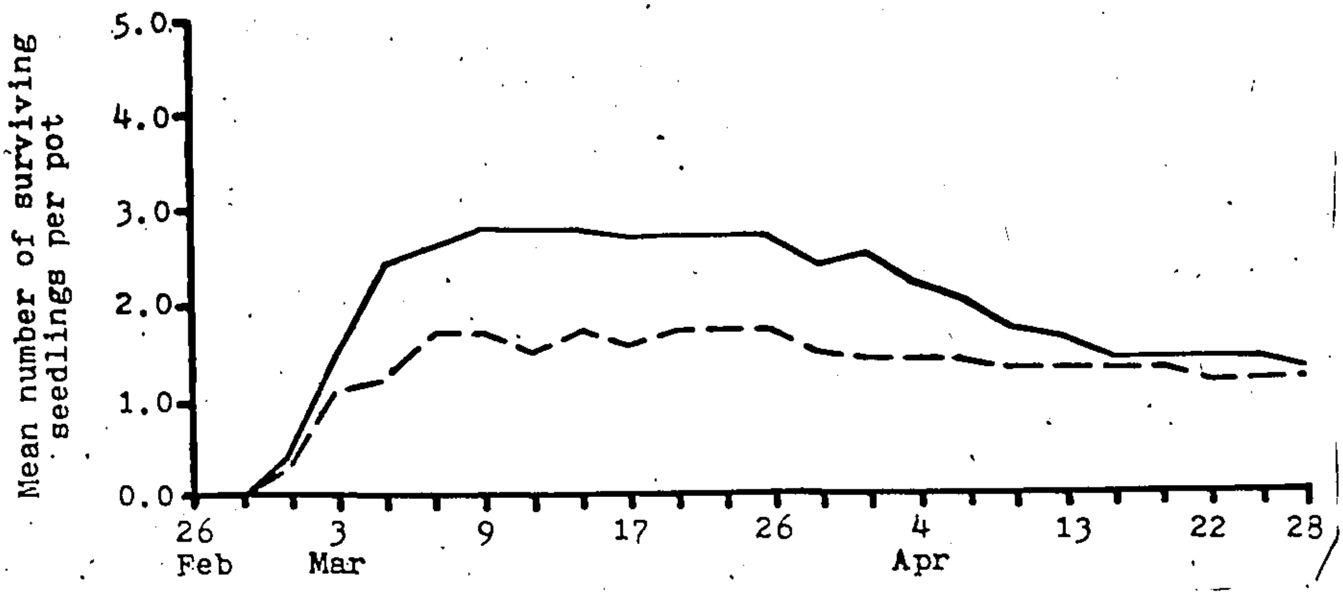


Fig. 5.6. Comparison of the mean survival on the control and fertilized tailings in the NPK experiment. ——— ; control; — — — ;NPK.

approach that of the control group. The reduced rate of mortality of the NPK group may have been due to their heightened vigour (Table 5.10). In the control group, the S- performed significantly better than did the S+. It may be that the nutrient supply of the S+ tailings had been depleted *in situ* by the overlying *S. pestifer* individual. Analysis of the tailings material found exchangeable Ca and Na concentrations to be significantly lower in S+ samples than in S- samples. No significant difference was observed in relation to Mg, K or P. Other nutrients, such as N, may be involved. The poor performance of the uncompacted B tailings was improved with the addition of the fertilizer. However, it remained significantly inferior to the S+ and S- samples. This suggests the operation of additional limiting factor(s) within the B tailings material, since the environment of the growth chamber was acceptably uniform and rerandomization was regularly enforced.

	Uncompacted			Compacted	
	Control	NPK	Ratio	Control	NPK
S+	46.5	727.6	15.6	0	0
S-	64.2	235.0	3.7	6.8	0
B	12.4	47.6	3.8	0	0
Overall	41.0	336.7	8.2	2.3	0

Table 5.10. Mean dry weights (mg) of the NPK experiment survivors.

It is imperative to note the extraordinarily poor performance on the compacted tailings irrespective of the nutrient treatment. Only a single, small plant (6.8 mg) survived, this on the slightly compacted S9h- control sample. No germination/emergence was observed at all in B4c (control or NPK) and in B6e (NPK). On the latter's control counterpart and on both treatments of S6g+ and B3h a maximum of only 1 or 2 seedlings was seen on each, and these died rapidly, only partly emerged. Three seedlings were observed on the slightly compacted S9h- (NPK), but these too died, though two had fully emerged. On its control counterpart, S9h-, 100% germination occurred. However, only the single plant survived, the other 4 having died, 2 fully emerged, 2 partly. It would seem, therefore, that while the application of NPK fertilizer significantly improves performance, it is vital to amend the physical substrate beforehand.

In Blakeman's (1976) in situ study, S. pestifer also displayed superior plant development in fertilized beds than in non-fertlized beds, although the rate of germination was "essentially equal" in both.

The augmented biomass produced through the addition of the NPK fertilizer may, _in situ_, improve the tailings environment in a number of ways:

i. increase the organic matter accumulation in the substrate (though it may be more economical to apply organic matter directly);
ii. better intercept air and water borne waste particles due to its greater mass and increased branching;
iii. better anchor the waste particles with its denser root network;
iv. reduce groundwater contamination through heightened evapotranspiration.

The enhanced vegetative growth may also extend to its reproductive capacity, which, if one extrapolates, would accelerate the establishment of a dense vegetative cover.

5.3. Hypotheses Revisited.

It is necessary at this point to consider the two hypotheses. To review, these are:

i. the bare areas are amenable to _S. pestifer_ ecesis but have not received its seed;
ii. the bare areas have properties antagonistic to _S. pestifer_.

Given the limited area of the tailings strip, the efficient dispersal mechanism of _S. pestifer_, the species' prodigious seed production (though this may be somewhat depressed in this population due to the adverse environment), and the presence of numerous _S. pestifer_ individuals both on the amended tailings surrounding the strip and on the strip itself, often adjacent to the bare plots, it would seem unlikely that sites 25+ m^2 in area, i.e. the B plots, did not receive any seed. Rather the absence of S. pestifer from the B plots is more likely attributable to antagonistic environmental properties. The consistently inferior performance of the B samples in the productivity, sawdust and NPK experiments, under the acceptably uniform macro-environmental, i.e. non-tailings, conditions of the growth chamber, not only supports this contention, but also infers that the limiting factor(s) occur in the tailings material itself. Both compaction prior to emergence or in the absence of advantageous microrelief and/or substrate cracking and insufficient available N, P and K were found to be detrimental to S. pestifer ecesis. Seasonal inundation, to which four of the B plots are subject, was also observed to be restrictive. However, the data indicate the operation of additional limiting factor(s) in these sites. A darkly coloured substrate, as occurs in B2, may also be deleterious, though verification is required.

In marked contrast is the micro-bare, S-, group, which either outperformed the S+ samples (in the productivity experiment, irrespective of the sowing depth, and in the NPK experiment under the control treatment) or fared comparably well (in the sawdust experiment under the control treatment). It would seem, therefore, that the S- tailings are capable of supporting S. pestifer. The species' absence from these sites may indicate the operation of antagonistic macro-environmental factors.

However, the field reconnaissance detected no evidence to support this. There were no apparent differences between the S- and the proximate S+ sites. It is unlikely that allelopathy is a factor, since S. pestifer individuals were observed in sufficiently close proximity for their branches to intertwine. Given the foregoing, the stochastic character of natural seed dispersal, the improbability of attaining a ubiquitous seed cover and the small size of the S- sites, it is suggested that the S- sites are devoid of S. pestifer due to the absence of viable seed for the current growing season.

6. Conclusion.

At the outset of this study it was suggested that the establishment of an extensive and dense vegetative cover on the tailings strip, desirable so as to moderate the associated environmental deterioration, could be most readily achieved through the expansion and intensification of the local S. pestifer population. Accordingly, the species micro-distribution was examined in relation to a number of environmental parameters. The basic question - why are the bare areas uncolonized by S. pestifer - was addressed and two hypotheses proposed, the absence of seed and the presence of limiting factors. The data collected in the field and in the laboratory support the conclusion that the B plots (large-scale bare areas) possess properties antagonistic to S. pestifer ecesis. A number of the parameters examined may be deleterious, including:

i. seasonal inundation;
ii. excessively dark substrate colour;
iii. compaction prior to establishment or in the absence of advantageous microrelief and/or substrate cracking;
iv. insufficient available N, P and K.

The operation of additional limiting factor(s) was also suggested, with the likelihood that these are in the tailings material itself. While it cannot be stated categorically, the data suggest that the S- (small-scale bare areas) are amenable to S. pestifer ecesis, but have not received viable seed for the current growing season.

The present study was limited in scope and design, due largely to the constraint of a single growing season during which to examine the S. pestifer distribution in relation to environmental conditions. An examination extending over several growing seasons would provide a more exact assessment. Seed rain, as well, could then be quantified. Errors incurred from anomalous conditions, such as the unusually dry weather over much of the growing season examined, would be reduced. The properties of the tailings material may also be subject to temporal variation. Further exploration for macro-environmental limiting factors, if any, operating in the S- sites is required. It would be interesting to observe the effect of inundation in situ in order to assess the applicability of the laboratory growth experiment observations. As previously stated, the influence of differential albedo merits additional investigation. Similarly, the mechanism(s) whereby S. pestifer is established in compacted tailings in situ requires confirmation. Since the operation of additional limiting factors was suggested by the data, further experimentation, ideally with field confirmation, is required in order to identify them and the degree to which they are influential.

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APPENDIX A

Sample	Distance[1] S+ to S-	# plants/ quadrat	% cover/ quadrat	Distance[1] S+ to neighbor	Dry weight[2]
S1a+	25	1	6.2	36.5	1.1
S1b+	25	2	3.1	11.0	<0.1
S1c+	25	1	12.5	14.0	1.4
S1d+	25	1	18.7	25.0	3.0
S1e+	25	1	25.0	16.1	4.7
S1f+	25	1	3.1	13.0	<0.1
S1g+	45	1	12.5	13.5	2.2
S1h+	25	2	25.0	0.0	1.1
S2a+	25	3	6.2	0.2	0.2
S2b+	25	8	43.7	0.0	0.8
S2c+	25	5	6.2	7.0	<0.1
S2d+	25	3	6.2	11.0	<0.1
S2e+	25	10	12.5	0.2	<0.1
S2f+	25	10	6.2	0.2	<0.1
S2g+	25	2	6.2	0.0	0.4
S2h+	25	4	6.2	8.0	<0.1
S3a+	37	3	3.1	0.0	<0.1
S3b+	25	2	25.0	2.5	1.8
S3c+	25	1	3.1	19.5	0.2
S3d+	39	1	3.1	40.0	<0.1
S3e+	25	2	6.2	4.0	<0.1
S3f+	44	2	12.5	0.0	0.6
S3g+	25	2	3.1	0.0	<0.1
S3h+	25	4	12.5	0.0	0.5
S4a+	46	1	3.1	22.0	<0.1
S4b+	25	2	3.1	13.0	<0.1
S4c+	25	3	3.1	11.5	0.2
S4d+	25	3	6.2	11.0	<0.1
S4e+	25	15	12.5	1.0	0.5
S4f+	25	3	6.2	6.5	0.2
S4g+	25	3	3.1	5.0	<0.1
S4h+	46	2	6.2	8.0	<0.1
S5a+	25	11	18.7	2.0	0.6
S5b+	25	9	31.2	0.0	0.4
S5c+	33	1	6.2	23.0	0.3
S5d+	25	3	50.0	0.0	5.8
S5e+	25	2	37.5	0.0	3.0
S5f+	25	6	25.0	0.0	0.5
S5g+	25	31	31.2	0.0	0.2
S5h+	25	4	50.0	0.0	2.4

[1] distance in cm

[2] dry weight in g

Sample	Distance[1] S+ to S-	# plants/ quadrat	% cover/ quadrat	Distance[1] S+ to neighbor	Dry weight[2]
S6a+	25	2	6.2	0.0	0.5
S6b+	62	2	6.2	5.0	0.2
S6c+	70	3	6.2	0.0	0.2
S6d+	44	1	3.1	11.0	0.3
S6e+	25	4	12.5	1.5	0.4
S6f+	25	1	3.1	16.5	<0.1
S6g+	51	1	3.1	13.0	<0.1
S6h+	25	2	12.5	0.0	0.6
S7a+	25	2	18.7	1.0	1.1
S7b+	25	1	3.1	13.5	<0.1
S7c+	25	4	12.5	0.5	0.9
S7d+	25	9	31.2	0.0	0.8
S7e+	25	1	3.1	6.0	<0.1
S7f+	25	2	12.5	1.0	0.6
S7g+	25	1	6.2	10.5	0.8
S7h+	25	1	3.1	51.0	<0.1
S8a+	25	1	3.1	27.0	<0.1
S8b+	25	2	3.1	0.3	<0.1
S8c+	25	1	100.0	0.0	50.6
S8d+	25	2	6.2	2.5	<0.1
S8e+	65	3	68.7	0.0	8.6
S8f+	25	1	6.2	21.5	0.4
S8g+	25	1	100.0	0.0	27.3
S8h+	26	2	3.1	6.5	<0.1
S9a+	25	4	18.7	1.0	0.5
S9b+	29	6	18.7	1.0	0.7
S9c+	25	4	6.2	0.0	0.2
S9d+	25	2	6.2	5.5	0.2
S9e+	25	2	12.5	1.0	0.7
S9f+	25	2	18.7	6.5	0.7
S9g+	55	6	12.5	0.2	0.2
S9h+	25	1	6.2	13.5	0.6
S10a+	25	2	12.5	0.3	1.1
S10b+	25	2	25.0	0.0	2.6
S10c+	25	1	62.5	14.0	12.9
S10d+	25	1	3.1	12.5	0.4
S10e+	25	1	6.2	6.5	0.8
S10f+	25	1	3.1	11.5	<0.1
S10g+	25	1	12.5	9.0	1.0
S10h+	25	2	31.2	1.0	2.0

[1] distance in cm

[2] dry weight in g

APPENDIX B

Sample	Compaction	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)*					C.E.C. meq/100g
					Ca	Mg	K	Na	H	
S1g+	x	sand	8.2	0.87	10.75	0.83	0.08	0.03	0.0	11.69
S1d+	x	sand	7.7	0.87	10.75	1.67	0.08	0.03	0.0	12.53
S1e+	nd	sand	8.1	T	9.75	1.25	0.08	0.05	0.0	11.13
S1f+	x	sand	8.2	T	11.25	0.83	0.08	0.26	0.0	12.42
S1g-	x	sand	8.2	T	10.75	0.83	0.08	0.03	0.0	11.69
S1d-	x	sand	8.0	T	12.25	0.79	0.10	0.04	0.0	13.18
S1e-	nd	sand	8.0	T	13.00	0.75	0.10	0.04	0.0	13.89
S1f-	x	sand	8.2	0.87	11.75	0.83	0.09	0.03	0.0	12.70
B1a	nd	sand	8.1	T	12.25	0.83	0.10	0.03	0.0	13.21
B1h	nd	sand	8.3	T	11.00	0.83	0.11	0.04	0.0	11.98
B1e	x	sand	7.9	T	12.50	0.42	0.09	0.03	0.0	13.04
B1b	x	sand	8.2	T	12.75	0.83	0.13	0.04	0.0	13.75
S2g+	x	sand	8.2	T	13.25	0.42	0.10	0.03	0.0	13.80
S2h+	x	sand	7.9	T	12.75	0.83	0.10	0.04	0.0	13.72
S2c+	x	sand	7.9	T	12.25	0.83	0.10	0.03	0.0	13.21
S2f+	nd	sand	8.0	T	12.50	0.42	0.10	0.03	0.0	13.05
S2g-	nd	sand	8.2	T	13.25	0.83	0.10	0.04	0.0	14.22
S2h-	x	sand	7.8	T	16.00	0.75	0.13	0.04	0.0	16.92
S2c-	x	sand	7.6	T	12.25	0.83	0.10	0.04	0.0	13.22
S2f-	nd	sand	7.6	0.87	15.50	0.67	0.10	0.04	0.0	16.31
B2e	x	sand	7.5	T	12.00	1.67	0.12	0.03	0.0	13.82
B2h	x	sand	6.3	T	9.75	2.50	0.08	0.04	0.0	12.37
B2a	x	sand	6.5	T	10.50	0.83	0.06	0.03	0.0	11.42
B2f	nd	sand	7.3	T	10.00	1.67	0.08	0.05	0.0	11.80

* with NH_4OAc (pH 7.0)

Sample	Compaction	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)* Ca	Mg	K	Na	H	C.E.C. meq/100g
S3f+	✓	clay	8.0	T	17.00	2.50	0.28	0.04	0.0	19.82
S3g+	nd	clay	8.1	T	23.50	2.08	0.28	0.03	0.0	25.89
S3d+	✓	clay	8.1	T	16.50	2.92	0.31	0.04	0.0	19.77
S3a+	nd	clay	7.8	T	18.75	2.08	0.33	0.03	0.0	21.19
S3f-	✓	clay	7.8	T	18.00	1.50	0.19	0.11	0.0	19.80
S3g-	nd	clay	8.0	T	21.00	2.42	0.26	0.22	0.0	23.90
S3d-	✓	clay	7.9	T	17.25	2.92	0.33	0.05	0.0	20.55
S3a-	nd	clay	7.8	T	18.50	1.67	0.28	0.03	0.0	20.48
B3d	nd	clay	8.2	T	18.00	4.58	0.33	0.10	0.0	23.01
B3e	✓	clay	8.0	T	23.50	4.17	0.41	0.12	0.0	28.20
B3f	✓	clay	8.2	T	15.25	2.92	0.26	0.03	0.0	18.46
B3h	✓	clay	8.1	T	18.50	3.75	0.36	0.17	0.0	22.78
S4e+	nd	clay	8.1	T	17.75	2.50	0.18	0.06	0.0	20.49
S4g+	✓	clay	8.1	T	17.25	4.58	0.49	0.13	0.0	22.45
S4a+	✓	clay	8.1	T	19.00	4.58	0.56	0.22	0.0	24.36
S4b+	✓	clay	8.1	T	19.25	3.75	0.36	0.08	0.0	23.44
S4e-	✓	clay	8.2	T	19.00	4.50	0.51	0.43	0.0	24.44
S4g-	✓	clay	8.1	T	20.00	8.33	0.61	0.39	0.0	29.33
S4a-	✓	clay	8.3	T	24.00	3.00	0.26	0.22	0.0	27.48
S4b-	x	clay	8.1	T	16.25	2.50	0.15	0.06	0.0	18.96
B4d	✓	clay	8.0	T	16.00	3.75	0.36	0.11	0.0	20.22
B4h	✓	clay	8.3	T	23.50	12.50	0.72	0.78	0.0	37.50
B4c	✓	clay	8.2	T	26.00	4.58	0.77	0.17	0.0	31.52
B4e	nd	clay	8.3	T	28.50	10.00	0.97	0.52	0.0	39.99

* with NH_4OAc (pH 7.0)

Sample	Compaction	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)*					C.E.C. meq/100g
					Ca	Mg	K	Na	H	
S5g+	✓	clay	7.9	T	17.75	5.00	0.69	0.61	0.0	24.05
S5a+	✓	clay	7.8	1.75	17.25	3.75	0.46	0.22	0.0	21.68
S5e+	nd	clay	7.8	T	16.50	3.33	0.54	0.26	0.0	20.63
S5b+	nd	clay	7.9	T	17.50	5.83	0.46	0.87	0.0	24.66
S5g-	✓	clay	8.0	T	16.50	5.42	0.51	0.70	0.0	23.13
S5a-	✓	clay	8.0	T	19.00	3.67	0.51	0.65	0.0	23.83
S5e-	nd	clay	7.9	T	18.25	3.33	0.36	0.43	0.0	22.37
S5b-	nd	clay	8.0	T	26.50	11.67	1.00	1.39	0.0	40.56
B5e	✓	clay	8.0	T	16.25	3.33	0.38	0.26	0.0	20.22
B5d	nd	clay	8.2	0.87	17.50	3.75	0.46	0.22	0.0	21.93
B5c	✓	clay	8.1	T	27.00	5.42	0.64	0.43	0.0	33.49
B5g	nd	clay	8.3	T	17.00	2.92	0.31	0.10	0.0	20.33
S6a+	nd	sand	8.1	T	11.75	0.83	0.12	0.04	0.0	12.74
S6h+	x	clay	8.1	0.87	17.00	3.33	0.33	0.30	0.0	20.96
S6g+	✓	clay	8.1	T	26.50	4.17	0.51	0.30	0.0	31.48
S6e+	✓	clay	8.1	T	26.50	4.58	0.44	0.30	0.0	31.82
S6a-	nd	sand	8.1	T	11.75	0.83	0.11	0.04	0.0	12.73
S6h-	✓	clay	8.0	T	21.00	2.17	0.26	0.22	0.0	23.65
S6g-	✓	clay	8.4	T	29.50	3.00	1.03	1.09	0.0	34.62
S6e-	✓	clay	8.2	T	26.00	4.17	0.51	0.22	0.0	30.90
B6e	✓	clay	8.2	T	30.00	10.00	0.69	0.48	0.0	41.17
B6d	✓	clay	8.1	T	36.50	9.17	1.79	0.39	0.0	47.85
B6g	✓	clay	8.2	T	32.50	9.17	0.77	0.43	0.0	42.87
B6b	✓	clay	8.3	T	39.00	13.33	0.87	0.61	0.0	53.81

* with NH_4OAc (pH 7.0)

Sample	Compaction	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)*					C.E.C. meq/100g
					Ca	Mg	K	Na	H	
S7g+	x	silt	8.5	0.87	14.00	1.67	0.13	0.03	0.0	15.83
S7a+	x	silt	8.0	0.87	14.25	0.83	0.13	0.04	0.0	15.25
S7f+	x	silt	8.5	0.87	14.00	5.00	0.41	0.10	0.0	19.51
S7b+	nd	silt	8.2	0.87	14.25	1.25	0.13	0.04	0.0	15.67
S7g-	x	silt	8.2	T	16.00	0.96	0.19	0.11	0.0	17.26
S7a-	x	silt	8.1	2.62	16.75	0.71	0.19	0.11	0.0	17.76
S7f-	x	silt	8.5	T	14.75	4.58	0.54	0.26	0.0	20.13
S7b-	nd	silt	8.2	2.62	16.00	0.87	0.19	0.11	0.0	17.17
B7c	x	silt	8.5	T	13.75	2.50	0.33	1.13	0.0	17.71
B7a	x	silt	8.3	T	14.75	1.67	0.36	0.70	0.0	17.48
B7b	x	silt	8.7	T	13.50	2.50	0.44	1.83	0.0	18.27
B7g	x	silt	8.4	T	13.75	2.08	0.26	0.96	0.0	17.05
S8h+	x	silt	8.0	1.75	12.75	1.25	0.16	0.03	0.0	14.19
S8g+	nd	silt	8.0	T	17.00	1.67	0.16	0.03	0.0	18.86
S8f+	x	silt	8.2	T	14.50	1.67	0.23	0.04	0.0	16.44
S8c+	x	silt	8.2	T	13.50	0.83	0.15	0.03	0.0	14.51
S8h-	x	silt	8.3	T	17.00	0.92	0.32	0.22	0.0	18.46
S8g-	nd	silt	7.9	T	17.25	1.25	0.16	0.04	0.0	18.70
S8f-	x	silt	8.2	T	17.25	1.67	0.26	0.06	0.0	19.24
S8c-	x	silt	8.1	T	17.25	0.75	0.26	0.11	0.0	18.37
B8a	nd	clay	8.3	T	18.00	4.17	0.46	0.56	0.0	23.19
B8b	x	silt	8.7	T	17.75	5.00	0.59	0.56	0.0	23.90
B8h	x	silt	8.4	T	18.75	3.75	0.33	0.61	0.0	23.44
B8c	✓	silt	8.1	T	15.00	1.25	0.15	0.30	0.0	16.70

* with NH_4OAc (pH 7.0)

Sample	Compaction	P.S.A.	pH	Avail. P (ppm)	Exchangeable cations (meq/100g)* Ca	Mg	K	Na	H	C.E.C. meq/100g
S9f+	✓	clay	8.2	T	17.00	3.33	0.36	0.35	0.0	21.04
S9a+	✓	clay	7.9	T	15.25	2.92	0.28	0.22	0.0	18.67
S9g+	✓	clay	8.1	T	15.75	2.92	0.38	0.10	0.0	19.15
S9h+	nd	clay	8.2	T	17.25	2.92	0.28	0.08	0.0	20.53
S9f-	✓	clay	8.2	T	nd	nd	nd	nd	0.0	nd
S9a-	✓	clay	7.8	T	26.50	3.75	0.49	0.26	0.0	31.00
S9g-	nd	clay	8.2	T	19.00	2.92	0.26	0.22	0.0	22.40
S9h-	✓	clay	8.0	T	20.00	3.00	0.38	0.22	0.0	23.60
B9c	✓	clay	8.3	T	31.00	8.33	0.41	0.35	0.0	40.09
B9g	nd	clay	8.2	T	35.00	8.33	0.44	0.39	0.0	44.16
B9f	x	clay	8.4	T	13.00	1.25	0.12	0.05	0.0	14.42
B9d	nd	clay	8.2	T	32.00	5.42	0.51	0.35	0.0	38.28
S10g+	x	sand	8.1	T	12.50	0.42	0.09	0.05	0.0	13.06
S10h+	x	sand	7.9	T	14.00	0.83	0.11	0.03	0.0	14.97
S10b+	nd	sand	7.9	T	11.50	0.83	0.10	0.03	0.0	12.46
S10f+	x	sand	7.9	T	16.50	0.83	0.09	0.03	0.0	17.45
S10g-	x	sand	7.9	T	15.00	0.75	0.10	0.04	0.0	15.89
S10h-	x	sand	7.8	T	14.00	0.83	0.11	0.03	0.0	14.97
S10b-	x	sand	7.9	T	16.75	1.04	0.13	0.04	0.0	17.96
S10f-	nd	sand	7.8	T	14.00	0.83	0.11	0.04	0.0	14.98
B10f	nd	sand	7.8	T	6.50	2.08	0.14	0.05	0.0	8.77
B10g	x	sand	7.8	T	14.50	1.25	0.15	0.04	0.0	15.94
B10h	nd	sand	7.9	T	14.25	1.67	0.19	0.22	0.0	16.33
B10e	x	sand	7.9	T	16.00	2.50	0.14	0.11	0.0	18.75

* with NH_4OAc (pH 7.0)