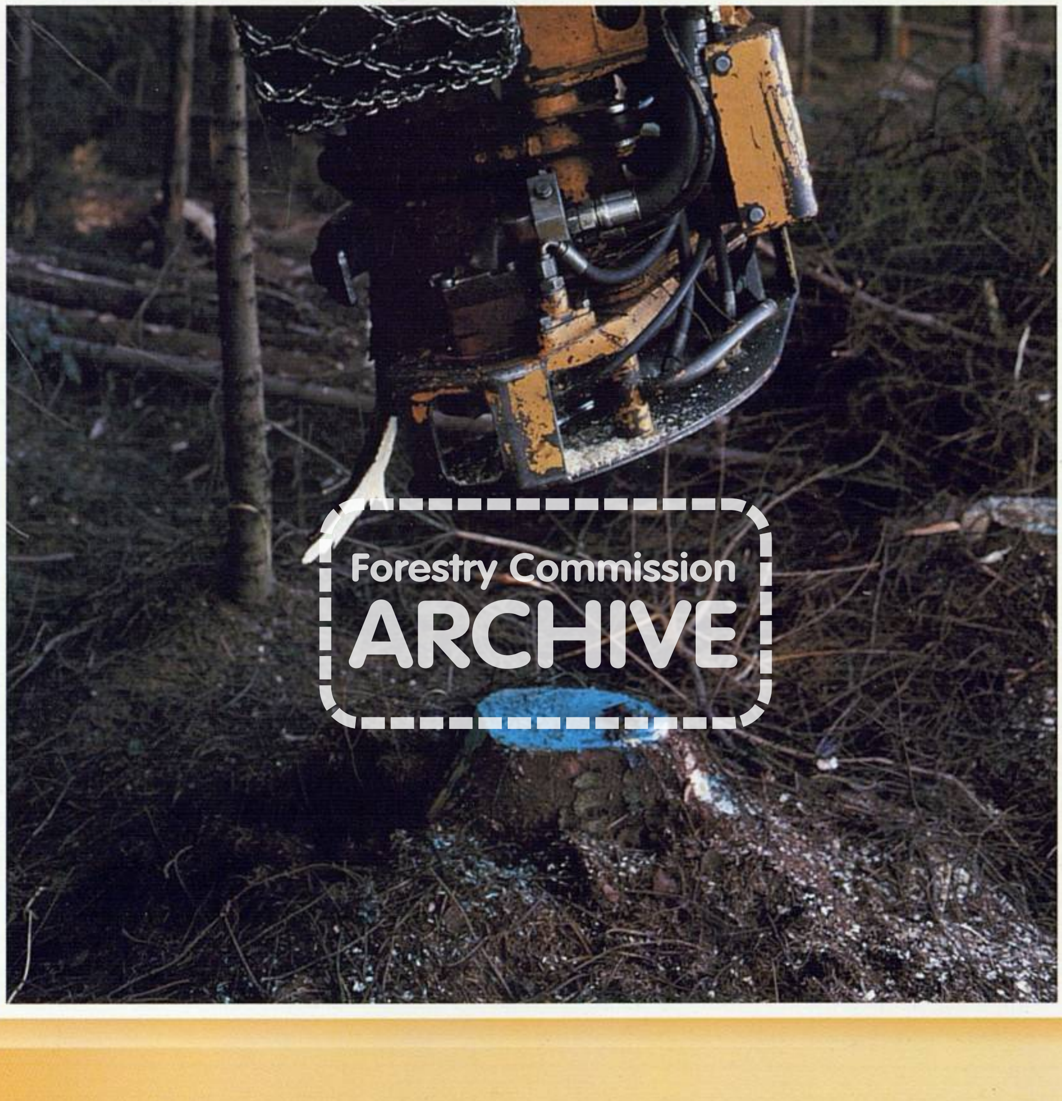
Forestry Commission

Borates for Stump Protection

A Literature Review

J. E. Pratt



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Borates for Stump Protection: A Literature Review

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Summary and object of review

The employment of borates for the control of a root- and butt-rotting disease caused by the basidiomycete fungus *Heterobasidion annosum* is reviewed in relation to the history of their uses in wood preservatives, their efficacy as stump treatment materials, and their effect on the environment.

A review of over 80 published experimental results from North America and Europe suggests that two borate compounds, namely borax and disodium octaborate, are equally effective at controlling *H. annosum* when applied to stumps as powder or as liquid solutions with concentrations above 5 per cent. Data on the effect that either substance at high concentration would have on the environment are limited, and largely relate to arid areas. However, neither substance is considered to pose a threat to the British environment with respect to its use.

This review was written originally as a source document for an application for approval of borates for stump treatment. It seeks to address some of the requirements specified in Article 4.1(b) of EC Council Directive 91/414/EEC on the Placing of Plant Protection Products on the Market, namely effectiveness, phytotoxicity, vertebrate toxicity, and environmental impact.

Borates

Sources

Boron (B) is a non-metallic element with atomic weight 10.8. It does not occur free in nature but always in combination with oxygen (= borate), and with other elements, notably sodium or calcium. The boron content of soils (2-100 ppm) varies with the boron content of parent materials, and is highest in sedimentary shales, sandstones and limestones and lowest in igneous rocks (Shorrocks, 1984). Commercially exploitable deposits exist in arid areas where evaporative concentration of soluble minerals has occurred. Such deposits occur in China, Russia, Turkey, South America and California, USA. It is estimated that natural weathering releases some 360 000 tonnes of boron into the environment each year (Butterwick *et al.*, 1989).

Chemical forms

Refined borates that are commonly in use today include:

- sodium tetraborate decahydrate (borax) $Na_2B_4O_7.10H_2O$: [36.5% B_2O_3 (boric oxide), 11.3% B (boron)]
- boric acid H_3BO_3: [56.3% B_2O_3, 17.5% B]
- disodium octaborate tetrahydrate $Na_2B_8O_{13}.4H_2O$: [67.1% B_2O_3, 20.8% B]

Borax and disodium octaborate are the two forms of borates most commonly associated with stump treatment against *H. annosum*. They differ in solubility and in pH of aqueous solution. At 20°C, disodium octaborate is twice as soluble as borax (9.5 compared with 5.1 parts per 100 parts saturated solution). The pH of borax is almost constant at pH 9.25 over a wide range of concentrations, whereas the pH of disodium octaborate falls with increasing concentration, from pH 8.5 at 1% w/w to pH 7.3 at 15% w/w.

Industrial uses

Borates have a wide variety of industrial, domestic, pharmaceutical and agricultural uses. In North America and Western Europe, over 200 000 tonnes of boron are used each year (Butterwick *et al.*, 1989). In this review, only two industrial applications are considered: their uses as wood preservatives and as agricultural fertilisers.

Use as wood preservatives

Borates have been used as wood preservatives for more than 50 years (Thornton, 1964). Impregnation by diffusion of building timbers began in Australia, during the Second World War (Anon., 1969) to control wood decaying fungi and boring insects. Diffusion utilises the water present in green timber as a vehicle for the dissolved borates, which are applied to the outer surface by spraying, dipping, or brushing. The borate travels inwards in solution from the zone of high concentration on the surface, the rate of diffusion being positively related to the initial moisture content of the substrate and to the concentration of the borate solution. An advantage of diffusion is that it does not need expensive equipment and is effective even with impermeable species such as hemlock and spruce. A disadvantage is that the borates are not chemically fixed in the wood, which is therefore suitable only for internal or protected situations.

The British standard for the concentration of borates diffused into building timbers requires a minimum cross-sectional retention of 0.4% m/m H_3BO_3 in oven-dry wood (Anon., 1986), which is easily achieved with the recommended charge retention of 5.3 kg H_3BO_3 equivalent per m^3 of green wood. Borates do not discolour timber, but are easily detected in treated wood by chemical assay or by a reaction with chromogenic reagents, most commonly one containing curcumin (Smith and Williams, 1969), which colours red in the presence of more than 0.2% boric acid equivalent.

Useful bibliographies on the use of boron compounds in timber preservation have been published by Cockcroft and Levy (1973), Bunn (1974), and Dickinson and Murphy (1989).

Use as fertilisers

Boron is an essential plant nutrient. When used as fertilisers for rectifying deficiency in agricultural, forestry, and horticultural crops, annual applications of borates at 4 kg B per ha are not uncommon, whereas up to 6 kg B per ha are occasionally applied to forest trees and to fruit and nut crops (Shorrocks, 1984). Boron fertiliser is widely used in tropical forestry plantations (Evans, 1992).

Both borax and disodium octaborate are commonly used in the manufacture of compound or mixed fertilisers. They are in the 'non-harmful' category according to the EEC

Directive on the Packaging and Labelling of Dangerous Substances, and no special precautions are normally required in their use. Where liquid and suspension fertilisers are needed, disodium octaborate is the preferred substance because it is the more soluble, and causes smaller changes in the temperatures of crystallisation (Shorrocks, 1984).

Boronated fertilisers have been regularly applied in Britain to arable crops (beets, brassicas) on light soils since the 1920s. Current annual application is estimated to be about 2 kg B per ha, on some 60 000 ha (Borax Consolidated Ltd., pers. comm., 1994). Boron is also sometimes applied as a fertiliser in irrigation water in Britain, where maximum rates of 2, 3 or 4 kg B per ha have been recommended as safe for 25 commonly grown agricultural, horticultural, and fruit crops that were ranked as sensitive, intermediate or tolerant to boron (Williams and Gostick, 1981).

In the Nordic forest ecosystems, boron levels in the soil were found to be generally low, especially towards the north and away from the coast (Wikner, 1983, 1985). Deficiencies occurred during periods of drought, or on organic soils. Fertilisation of pine and spruce stands with 1.7 kg B per ha is recommended (Braekke, 1983): toxic symptoms may develop at rates exceeding 4.5 kg B per ha.

Borates in the environment

Boron in the soil

Boron levels in soil are highly variable but rarely exceed 100 ppm. Boron is present in three forms: as part of silicate minerals, adsorbed on clay minerals and aluminium and iron hydroxides, and in organic matter. The physical nature of a soil can affect the availability of boron to plants. Wear and Patterson (1962) demonstrated that more boron was available to plants in a coarse-textured soil medium than in a fine-textured one. Boron availability is also influenced by soil pH, more boron being adsorbed by clay particles and rendered unavailable as pH rises (Peterson and Newman, 1976; Bohn *et al.*, 1985).

The few studies conducted on the mobility of boron in field soils complement results obtained from laboratory studies (Baker and Mortensen, 1966; Neary *et al.*, 1975; Crandall *et al.*, 1981; Sposito and Calderone, 1988).

Sodium borate compounds are known to be mobile and easily leached (Russell, 1988), especially under the saturated acid soil conditions that are common in upland Britain. Indeed, as early as 1939 Eaton and Wilcox demonstrated that much of the boron fixed in the soil can be desorbed using large quantities of water, a process that becomes harder with ageing of the fixed boron (Rhoades *et al.*, 1970).

Boron in water

In natural waters, boron forms stable and highly soluble compounds (H_3BO_3, $B(OH)_3$, $B(OH)_4^-$) and complex polyions (Butterwick *et al.*, 1989). Borates form ion pairs with major and minor cations whose stability constants decrease in the order Mg^{2+} >Ca^{2+} >Sr^{2+} >Li^+ >Na^+ (Raymond and Butterwick, 1992). Concentrations of boron in British surface waters are generally below 1 mg B per litre (Anon., 1980; Raymond and Butterwick, 1992). Higher concentrations have been found in streamwater where weathering of boron-rich deposits occurs, such as south-west USA where concentrations exceeding those found in the sea (4.5 mg B per litre) have been measured in freshwater without apparent detriment to local populations of otherwise sensitive aquatic vertebrates.

Boron budgets have been calculated for oceanic acidic upland streams in Wales and Scotland. In Wales, Neal *et al.* (1986) established baseline concentrations of boron in upland spruce plantations and streams of 1-10 and 2-15 µg B per litre in rainfall and streamwater respectively. Further studies (Neal *et al.*, 1992) demonstrated that boron content of upland streams was not strongly influenced by variations in streamflow. In the same general area, Durand *et al.* (1994) demonstrated that boron was in approximate balance with a dry-deposition input from the atmosphere of *c.*100 g per ha per yr, and a similar output in streamwater. The authors suggest that a net loss of boron occurs for at least two years after felling conifer overstoreys. In Scotland, Pratt *et al.* (in prep.) demonstrated an increase in streamflow boron following its application (as disodium octaborate) at 2 kg B per ha as a fungicide, mainly to stumps. They estimated that during the 20-week period of the trial, at least 0.25 kg B per ha was lost in drainage water. Boron concentrations in the streamwater were well below the statutory maxima set for freshwater and drinking water in the UK, and did not exceed 140 µg B per litre.

Ecotoxicology

Plants

Silicaceous borates are not available to plants, and measurement of total boron content of soils is of limited value in determining the toxic thresholds of this element in soils. However, as a general rule, the relationship between water-soluble soil boron and leaf boron tends to be roughly linear (Butterwick *et al.*, 1989). Clay-adsorbed boron is probably the major source for plants, although that which is associated with organic matter can, on mineralisation, also be an important source (Shorrocks, 1984). The primary role of boron in plant growth has yet to be established but, alone among the micronutrients, boron has not been identified as a component or as an activator of any enzyme (Shorrocks, 1984). Nor is boron apparently essential to the life of fungi (Bergmann, 1984). However, it is clear that an effect of boron shortage is a reduction in the absorption of phosphorus and other trace elements because of changes to the functioning of the plasmalemma of root cells.

Absorption of boron by plants from the soil is probably by a passive mass-flow mechanism, as unassociated boric acid (Sposito and Calderone, 1988). Thereafter, boron is highly mobile in xylem, and tends to become concentrated in the older tissues around the periphery of the moisture transport system (Guha and Mitchell, 1966; Neary *et al.*, 1975; Cameron and Ranee, 1984). Boron can also be absorbed through the leaves. Hanson (1991) showed that boron, applied as a foliar spray to some fruit crops in autumn before leaf senescence occurred, moved out of leaves into adjacent twigs and spurs. These reserves of boron remained in the wood until the following spring, when they were allocated to developing flowers. However, a continuous supply of boron from soil to roots is necessary, as few plants can redistribute boron from leaves to roots even when the latter are deficient (Adams, 1978).

Boron is known to be toxic to plants when present at higher than micronutrient concentration (J. D. Lloyd, pers. comm.), and indeed borax was previously registered as a herbicide (Anon., 1991). The symptoms of boron toxicity are similar in most plants, and consist of marginal and tip chlorosis to leaves, followed by necrosis (Shorrocks, 1984). Loss of yield is unusual, because of the localised nature of necrosis within leaves (Oertli and Kohl, 1962). The conditions that can lead to an excess of boron in plants or soil have been reviewed by Bergmann (1984) and Gupta *et al.* (1985). Because of the mobility of boron within both plants and soil, and because the difference between deficiency and excess of soluble soil boron is so slight, a small loading of extra boron on sandy soils is more likely to be phytotoxic than on clay soils or on soils with a high pH where excess boron would be rendered unavailable to plants. A loss of water through transpiration can lead to elevated levels of boron with a consequent rise in boron concentration in distal portions at the ends of veins, resulting in the typical pattern of damage. The rate of transpiration, being variable among species, may thus be a major determinant of boron tolerance where it influences the rate of boron accumulation within plants (Lang *et al.*, 1986).

Because boron is an essential micronutrient of arable crops, there are many more references to its phytotoxicity to herbaceous than to woody plants. In an early example Eaton (1944) established critical levels of water-soluble boron in soil growth-media for some 50 species of mainly arable crops. Data extracted from this paper are tabulated (see Table 1), and the crops ranked by leaf-boron content in five groups, each of which shows the lowest soil boron concentration at which toxicity was visible. The data serve to demonstrate both the wide range of boron tolerance exhibited by commonly grown plants and that the first signs of toxicity in the leaves of affected plants do not occur at a common level of boron.

Tolerance of some tree species to elevated levels of boron in soil contaminated by industrial fuel ash have been noted for Britain (Moffat and McNeill, 1994). As a general rule, however, boron toxicity to forest trees is uncommon (Stone, 1990) except perhaps in arid areas.

Aquatic organisms

Data on the toxicity of boron to aquatic organisms were reviewed by Butterwick *et al.* (1989) and by Raymond and Butterwick (1992). It is clear from these reviews that the most susceptible fish tested so far is rainbow trout (*Salmo gairdneri* Richardson), where in excess of 1 mg B per litre is required to obtain a 10% increase in control-adjusted mortality.

The absence of reliable data for indigenous UK fish and invertebrate species has led the Water

Table 1. Boron phytotoxicity: boron concentration in leaves in plants showing symptoms of toxicity when growing in soil media amended with the lowest concentration of boron that resulted in visible injury (calculated from Eaton, 1944)

Soil B: 1 ppm		*Soil B: 5 ppm*		*Soil B: 10 ppm*		*Soil B: 15 ppm*		*Soil B: 25 ppm*	
Crop	*Leaf ppm*	*Crop*	*Leaf ppm*	*Crop*	*Leaf ppm*	*Crop*	*Leaf ppm*	*Crop*	*Leaf ppm*
Poa pratensis	22	Maise	123	Radish	86	Alfalfa	516	Turnip	399
Sorghum	24	Peach	170	Radish	192	Sugar beet	521	Celery	720
Lettuce	70	Maize	179	Sugar beet	262	Beet	671		
Lettuce	75	Cherry	182	Carrot	324	Alfalfa	740		
Onion	91	Artichoke	236	Radish	337	Alfalfa	854		
Potato	98	Tomato	253	Tobacco	365				
Onion	104	Red pepper	328	Radish	407				
Onion	115	Californian poppy	377	Cabbage	440				
Navy bean	151	Carrot	395	Sugar beet	495				
Blackberry	210	Cowpea	404	Cotton	522				
Elm	277	Sweet pea	520	Sweet clover	602				
Lemon	314	Tomato	544	Sugar beet	612				
Persimmon	389	Pea	609	Beet	637				
Zinnia	436	Sorghum	625	Sweet clover	1164				
Jerusalem artichoke	519	*Calendula*	715						
		Fig	722						
		Muskmelon	923						
		Grape	926						
		Grape	1804						

Research Centre to propose single standards for Britain of 2.0 mg B per litre and 5.0 mg B per litre for the protection of freshwater fish and other aquatic life, respectively (Mance *et al.*, 1988). These standards are based on approximately one-tenth of the lowest concentration of boron recorded as producing a toxic effect in experimental studies. This contrasts with the United States Fish and Wildlife Service's recommended safe level of 1 mg B per litre for the protection of all aquatic life, based on a review of the literature which showed that representative species of aquatic plants, invertebrates, fish and amphibians could tolerate up to 10 mg B per litre for extended periods without harm (Eisler, 1990). The above boron criteria represent recommended values only. Boron is not covered in the relevant European Community Directive on the quality of freshwaters needing protection or improvement in order to support fish life (75/659/EEC).

Invertebrates

Borates are potent systemic poisons against a variety of insects when ingested at high concentration, and have been used to control cockroaches (*Blattella* spp.) (Ebling, 1989) and wood-boring beetles (Taylor, 1967). There are no data on the effect that the use of borates in the forest might have on indigenous woodland insects beyond anecdotal evidence from Rishbeth (1959) that the application of borates to stumps might control *Hylobius abietis* (L.). This seems unlikely in view of the low boron loading in treated stumps, and also the observations of Hodges (1970) that in the southern states of the USA a related species, *Hylobius pales* (Herbst), seemed to thrive in pine stumps that had been treated with dry borax.

Mammals

Acute oral toxicity of boric acid in the rat is LD_{50} 3000-4000 mg per kg bodyweight, and that of borax is LD_{50} 4500-6000 mg per kg body-weight (Weir and Fisher, 1972). These rates are above the threshold median LD_{50} of 2000 mg per kg bodyweight that defines a substance as dangerous (Directive 79/831/EEC, 18/09/1979). Borax is classified in WHO Class Table 5, EPA Toxicity Class III (Kidd and Hartley, 1991).

No evidence of carcinogenicity was noted from a full two-year bioassay on boric acid in mice at feed doses of 2500 and 5000 mg B per kg in the diet. Neither boric acid nor borax are mutagens in the Ames test (Anon., 1988). In humans, boric acid is excreted in urine with a half-life of 21 hours, and completely in 96 hours (Anon., 1988).

Butterwick *et al.* (1989) cite three studies on the effect of boron on grazing animals. Sheep developed enteritis when fed 40 mg B per kg or grazed on soil with high (30–300 mg B per kg) boron content. In the other two cases, cattle were exposed to high concentrations of boron in their drinking water, but showed no overt toxicosis at 120 mg B per litre. A safe level of 5 mg B per litre in drinking water for cattle in the USA has since been challenged, and an alternative maximum concentration of 40 mg B per litre has been suggested (Green and Weeth, 1977; Weeth *et al.*, 1981).

The toxicology of disodium octaborate is similar to that of boric acid and borax. All are poorly absorbed through intact skin, and are not skin or eye irritants (Anon., 1988). A long-term (eight-hour TWA) exposure limit to borax dust of 5 mg per m^3 has been set for Britain under COSHH Regulations, 1988. A similar threshold has been set in America (Anon., 1980).

An international symposium on the health effects of boron and its compounds was held in 1992 at the University of California at Irvine. A summary of the conference (Anon., 1992) does not suggest that the previous assessments of the hazards associated with boron compounds were materially wrong, and defines those areas where further research would be beneficial. The proceedings of the symposium are due for publication shortly.

European Community Directives relating to the quality of water intended for human consumption (80/778/EEC) and the quality required of surface water intended for the abstraction of drinking water (75/440/EEC) specify a guide value of 1 mg B per litre, which was recently confirmed as acceptable (Anon., 1995). No mandatory values are given. However, the British Water Supply (Water Quality) Regulations 1989 prescribe a maximum concentration of 2 mg B per litre as a level which must not be exceeded in drinking water. This level also applies to private water supplies under Water, England and Wales (Private Water Supplies) Regulations 1991.These contrast with recommended values of 0.5 mg B per litre in the former USSR and 1.0 mg B per litre in the US as safe levels for drinking water (Eisler, 1990).

Use of borates for control of *Heterobasidion annosum*

Chronology

The disease caused by *Heterobasidion annosum* is endemic throughout the coniferous forests of the Northern Hemisphere. Basidiospores, produced from perennial sporocarps throughout the year, may travel long distances in the air. If they alight on the exposed surface of a freshly cut conifer stump, they may cause an infection that can spread to neighbouring healthy trees by root contact. On some sites, trees of any age may be killed by the fungus. More commonly, the fungus gains entry into the base of an infected tree and decays the heartwood, often to a height of several metres, rendering the valuable butt log useless. It is the ability of the fungus to remain viable in diseased stumps for many years and thus infect young trees in subsequent rotations that makes this one of the most serious and intractable of forest diseases. The fungus is unable to live freely in the soil and is thus confined to woody tissues. Control of the disease caused by the fungus is achieved when the infection of stumps by airborne basidiospores is prevented by a prophylactic application of a fungicide to the stump soon after cutting.

The first description of the use of borates to control *H. annosum* was from Britain, by Rishbeth (1959). In trials on fresh pine stumps in Thetford Chase, he used disodium octaborate, applied as a 20% aqueous solution and as a dry powder. This material, which is manufactured as a solid solution of borax and boric acid, was a novel substance at the time Rishbeth initiated his trials: a patent for its manufacture was taken out in 1958, and published in 1961 (US patent 2 998 310). The advantages for wood preservation of such a mixture (high solubility and near neutral pH) had been described by Findlay (1953).

Rishbeth's work provided a stimulus for research into chemical control of the disease in the pine forests of the USA (Kuhlman *et al.*, 1976). In these early trials the chemical used was mainly borax, applied to stumps as a dry powder or in aqueous solutions of around 10% concentration (Driver 1963a,b; Sinclair, 1963; Berry and Bretz, 1964). The trials included artificial inoculation with basidiospores or with conidia, and were mostly successful.

In Britain, further trials on pine using disodium octaborate were conducted, and in 1964 the substance was described as being effective (Phillips, 1964). By 1966, the use of disodium octaborate was recommended for stump treatment in Britain in areas where domestic animals had free access (e.g. the New Forest and the Forest of Dean), in water catchment areas where the statutory water authorities objected to the use of other chemicals, and in plantations where direct supervision of labour was not possible (Anon., 1966). Quantities used, however, were small: in 1966, it was estimated that the Forestry Commission used 512 kg of disodium octaborate compared with 40 tonnes of sodium nitrite (D.A.Burdekin, pers. comm.): by 1974, disodium octaborate consumption had risen only to 600 kg.

By 1967, Rishbeth (1967) was able to review the advantages and disadvantages of disodium octaborate, and report on some long-term assessments. Disodium octaborate had the virtue of low mammalian toxicity, and was ideal for use in sensitive water-catchment areas. These views were reiterated by Burdekin (1968). A disadvantage is the tendency of all borates to come out of solution in cold weather. This problem had been recognised in the USA, where Berry (1965) found that 35% ethyl alcohol mixed with 10% borax lowered the freezing point without impairing the efficacy of the treatment.

In North America borax had proved effective when applied as a dry powder to resinous stumps of *Pinus* spp. in the southern states. In 1967, it was tested on less resinous conifers such as western hemlock (*Tsuga heterophylla* [Raf.] Sargent) in Washington State, and was found to be less effective, probably due to rain-washing of the powder from the sloping cuts of the stumps before diffusion allowed the chemical to gain entry into the stump tissues (Edmonds *et al.*, 1969). Results using borax in water or in a mixture of glycerol and alcohol appeared to provide better control and more satisfactory penetration of the stump tissues. In Vancouver, stumps of Douglas fir (*Pseudotsuga menziesii* [Mir.] Franco) and western hemlock were used by Weir (1969) to test seven substances incorporating borates including disodium octaborate as a 15% solution. This is the first report of the use of disodium octaborate on species other than pine. Weir rated the efficacy of each substance using a composite rating system: disodium octaborate was thought to be among the most effective, although results from trials on Douglas fir were poorer than those on western hemlock.

Although recommended for use in Britain as early as 1966, results of trials of disodium octaborate on species other than pine in Britain were not published until 1970 by Phillips and Greig (see below). In mainland Europe, stump treatment trials using borates were limited to Norway spruce (Schonhar, 1977, Marinkovic and Smit, 1978) or pine (Rosnev, 1983). They used solutions of borax at 10% or 20%, and described their experiments as successful. Trials by Fedorov *et al.* (1977) in Russia were also successful using 5% borax in solution on Scots pine stumps.

The first trials of borates on stumps cut by harvesting machines were reported in 1981 by Ross and Hodges, in the USA. Stump treatments were applied manually: disodium octaborate solutions (2.2% and 4.4%) by sprayer, and borax powder by shaker. The treatments were successful.

Some long-term reviews of the benefits of stump treatment were stimulated by a symposium held in California in 1989 on research and management of *H. annosum* in western North America (Otrosina and Scharpf, 1989).

A full risk-assessment for using dry borax for stump treatment in California (Kliejunas, 1991) concluded that there was no risk of acute toxicity to fish and wildlife as defined by current United States Environmental Protection Agency (EPA) criteria.

Approvals

There is no evidence that approval was sought for the use of disodium octaborate as a fungicide in British forests under the Pesticides Safety Precautions Scheme (PSPS) in 1966 when it was first recommended for use in Britain or in 1971 when approval was sought and obtained for the use of urea for stump treatment.

When marketed as Timbor by Borax Consolidated, disodium octaborate was approved for use as a wood preservative under PSPS at some time after 1975. When PSPS was superseded by the Control of Pesticides Regulations in 1986, the material was granted automatic approval by the Health and Safety Executive (HSE), the regulatory body, for use by the diffusion process at concentrations between 12% and 40% (HSE 3621). This approval was extended in December 1992 to cover the use of Timbor at concentrations of between 1% and 12% in vacuum/ impregnation timber preservation systems. In October 1992, Borax Consolidated submitted a full data package (ref HSE 1623) in response to the HSE Data Summary Call-In Notice No 52C for Review of Disodium Octaborate Tetrahydrate.

In 1976 in the USA, borax was quoted as being '. . . the only chemical currently registered for use as a stump treatment . . .' (Kuhlman *et al.*, 1976). An approval, issued to US Borax and Chemical Corp (EPA Reg No 1624-94), specifies the use of the material as a dry powder applied at rates of 1 pound per 50 square feet (0.1 kg per m^2) of stump. This approval was not renewed by US Borax, but was replaced by them with EPA Reg No 1624.39 for Timbor (disodium octaborate). The label specifies that Timbor can be used to control *Fomes annosus* in a 10% aqueous solution, along with its more traditional role in wood preservation.

Mode of action

Rishbeth (1959) showed that boron penetrated to 5 cm or more below the surface of treated, freshly cut pine stumps within a few hours. Thereafter it was depleted from above-ground tissues so that after two months it was hardly detectable there (i.e. >0.002% boron). He proposed that the original barrier to colonisation of stumps by basidiomycetes was toxic in nature. Thereafter, the lowering of boron concentration from the stump surface led to the establishment in the stump of fungal species (*Peniophora* spp., *Botrytis* spp., etc.) that were both more tolerant of boron and more competitive than *H. annosum.*

Research into possible modes of action of borates followed Rishbeth's suggestion of fungitoxicity. Johnson and Cowling (1965) considered the possibility that borates stimulated production of fungitoxic pinosylvin and its monomethyl ether in pine heartwood, but found that they do not. After extensive research, Koenigs (1969, 1971) established a toxic threshold for anhydrous sodium tetrahydrate of *c.* 300 ppm in wet pine wood, and observed that a rise in pH of treated wood was not the key factor that prevented the growth of *H. annosum.* In addition, Koenigs confirmed Rishbeth's observations on the movement of borates downwards from the treated surface of pine stumps, an effect subsequently demonstrated in Sitka spruce in Britain (Pratt and Quill, in prep.).

In their work, Johnson and Cowling (1965) tested the relative tolerance to borates of *Peniophora* spp. and *Trichoderma* spp., two potential competitors to *H. annosum* in treated stumps, and found that both tolerated higher borax loading in fresh pinewood stem sections than did *H. annosum*. However, Hadfield (1968) observed that in pine stumps treated with dry borax, *Trichoderma* spp. was rarely observed and that in many stumps all fungal growth was inhibited with the occasional exception of blue-staining fungi.

The effects of borates on tissues in stumps have been inadequately researched. Rishbeth (1959) observed that pine stumps treated with 20% disodium octaborate were killed rapidly, and soon dried out. Death of stump tissue was not measured in a trial of disodium octaborate on Sitka spruce stumps (Pratt and Quill, in prep.), but moisture content determinations over a period of a year after treatment did not reveal any differences in the rate of drying of stump wood in treated and untreated stumps.

An effect of inorganic borates on living tissue has been suggested by Lloyd *et al.* (1990) and J. D. Lloyd (pers. comm.) in which borates appear to undergo chelate formation with compounds containing polyhydric alcohol (polyols). It is likely that such complexation with compounds of biological importance is the mechanism by which borates act as biocides, biostats and wood preservatives. A result of this complex formation is the inhibition of cell oxidoreductase systems. Detrimental effects on cell membranes have also been implicated.

Efficacy trials

The reports of trials from 1959 onwards have involved the application of borates to freshly cut stump surfaces, followed at varying intervals by sampling. In nearly 80% of trials, stumps were inoculated either with conidia or basidiospores of *H. annosum* or with a mixture of the two. Conidia from laboratory cultures, or basidiospores from living sporocarps were suspended in water (usually sterilised and distilled) and applied to stump surfaces in drops or by sprayer at variable rates, often exceeding 0.5×10^6 spores per stump. Most commonly, the presence of infection was determined by incubation of discs cut from the treated stumps after an interval, usually of about six months. In some cases, disease that developed among neighbouring trees was assessed (see below).

Assessment of efficacy was usually made by comparing the incidence of *H. annosum* infection in treated and untreated control stumps. In a few cases, the area colonised was included as the main (e.g. Driver and Ginns, 1969) or as an additional measure of efficacy (e.g. Pratt and Quill, in prep.; Pratt, 1994). In one case, severity of infection was assessed by culturing from stumps that had been split longitudinally (Myren, 1974). The importance of measuring the areas of stumps that are colonised by the fungus was demonstrated by Morrison (1989).

An analysis of 85 reports of individual experiments which are available as published or internal reports was made (for a full list, see Table 2). The locations, species, borates used and the results of these trials are summarised in Tables 3-7.

The efficacy of treatments using borax either as a powder or in solution, and of disodium octaborate, were calculated from these reports, and expressed as the mean percentage incidence of infection in treated and in untreated stumps. These data include experiments using borax or disodium octaborate alone or in mixture with other substances (Table 5).

Experiments that used only borax or disodium octaborate are summarised in Table 6.

In most experiments, stumps were treated to run-off, which approximates to 1 litre of chemical per m^2 of stump surface area.

Although of heterogeneous origin, these combined data demonstrate a convincing efficacy of borate products in disease control.

Measures of efficacy other than those based on the incidence of colonised stumps were included in some trials. Rishbeth (1967) found that treatment of Scots pine stumps with 20% disodium octaborate failed to reduce disease in roots that were already infected when the trees were felled. Artman *et al.* (1969) reported that treatment of *Pinus taeda* (L.) stumps with dry borax significantly reduced the incidence of sporophores on treated compared to untreated stumps after a three-year incubation period. A similar result was reported from Ontario (Myren and Punter, 1972) where use of dry borax appeared to reduce sporophore production on treated *Pinus resinosa* (Aiton) stumps considerably after six years. A significant reduction in the spread of disease following treatment was reported by Witcher and Lane

Table 2a. Published efficacy data: borax

Author	*Date*	*Loc.*	*Spp.*	*Material*	*Conc. %*	*Inoc.*	*%T*	*%C*	*Reps.*	*Weeks*
Berry, Bretz	1964	USA	Pine	Borax+EA35	L 10	+	15	95	20	12
				Borax	L 10	+	8	95	40	12
Driver (A)	1963	USA	Pine	Borax	L 10	+	3	84	31	12
Driver (B)	1963	USA	Pine	Borax	L 5	+	0	26	32	24
				Borax	L 7.7	+	0	40	20	12
				Borax	L 10	+	3	90	37	30
				Borax	L 10	+	0	26	32	24
				Borax	L 10	+	0	30	30	12
Edmonds, Driver, etc	1969	USA	WH	Borax	L 10	–	0	100	10	17
				Borax	L 10	+	10	59	60	13
				Borax+Glyc	L 10	–	10	100	10	17
				Borax+Glyc	L 10	+	10	59	60	13
Morrison, Johnson	1975	Can.	DF	Borax	L 10	+	45	75	5	26
				Borax	L 10	–	26	63	10	26
			WH	Borax	L 10	+	35	70	5	26
				Borax	L 10	–	12	63	10	26
Rosnev	1983	Rus.	Pine	Borax	L 10	+	?	?	?	?
				Borax	L 20	+	?	?	?	?
Russell, Thompson, etc	1973	USA	WH	Borax+Sug	L 10	–	11	45	99	16
Schonhar	1977	Eur.	NS	Borax	L 10	+	4	58	120	26
Sinclair	1963	USA	Pine	Borax	L 10	+	0	95	92	?
Smith	1970	USA	Fir	Borax	L 10	+	4	55	200	10
Wallis, Morrison	1975	Can.	WH	Borax	L 10	?	11	70	80	26
Weidensaul, Plaugher	1966	USA	Pine	Borax	L 10	–	4	20	100	40
Weir	1969	Can.	WH	Borax	L 10	+	8	80	50	26
	1969		DF	Borax	L 10	+	10	84	50	26
Artman, Frazier, etc	1969	USA	Pine	Borax	P	–	4	57	230	150
Driver, (B)	1963			Borax	P	+	0	40	20	12
Driver, Ginns	1969			Borax	P	+	0	54	100	12
Edmonds, Driver, etc	1969	USA	WH	Borax	P	+	3	59	60	13
				Borax	P	–	29	59	75	20
				Borax	P	–	56	88	50	18
				Borax	P	–	20	100	10	17
Graham	1971	USA	Pine	Borax	P	–	0	3	300	12
				Borax	P	+	1	47	300	12
Hodges	1970	USA	Pine	Borax	P	+	1	53	120	36
	1974			Borax	P	–	0	24	25	52
Morrison, Johnson	1975	Can.	DF	Borax	P	–	22	63	10	26
			WH	Borax	P	–	18	63	10	26
Myren	1981	Can.	Pine	Borax	P	+	0	100	100	7
				Borax	P	–	0	54	100	7
Myren, Punter	1972	Can.	Pine	Borax	P	+	10	85	55	26
Nelson, Li	1980	Can.	WH	Borax	P	+	0	?	?	?
Russell, Thompson, etc	1973	USA	WH	Borax	P	–	3	45	99	16
Seaby	1973	GB	SS	Borax	P	+	2	71	42	20
Smith	1970	USA	Fir	Borax	P	+	0	55	100	10
Wallis, Morrison	1975	Can.	WH	Borax	P	?	20	78	40	26
Weir	1969	Can.	DF	Borax	P	+	19	84	50	26
			WH	Borax	P	+	4	80	50	26

Table 2b. Published efficacy data: disodium ocaborate tetrahydrate

Author	*Date*	*Loc.*	*Spp.*	*Material*	*Conc. %*	*Inoc.*	*%T*	*%C*	*Reps.*	*Weeks*
De Nitto	1993	USA	Pine	DOT	L 5	+	47	80	20	8
				DOT	P	+	21	80	20	8
Phillips, Greig	1970	GB	Pine	DOT	L 5	+	7	23	30	26
				DOT	L 10	+	10	23	30	26
			SS	DOT	L 5	+	10	17	30	11
				DOT	L 10	+	7	17	30	11
			Pine	DOT	L 5	+	0	40	30	11
				DOT	L 10	+	0	40	30	11
Phillips, Greig (Dam)[a]	1970	GB	Pine	DOT	L 5	+	20	40	15	26
				DOT	L 10	+	26	40	15	26
			SS	DOT	L 5	+	13	20	15	11
				DOT	L 10	+	0	20	15	11
			Pine	DOT	L 5	+	20	86	15	11
				DOT	L 10	+	0	86	15	11
Phillips, Greig (Del)[b]	1970	GB	Pine	DOT	L 5	+	6	20	15	26
				DOT	L 10	+	6	20	15	26
			SS	DOT	L 5	+	25	25	15	11
				DOT	L 10	+	27	27	15	11
			Pine	DOT	L 5	+	13	60	15	11
				DOT	L 10	+	6	60	15	11
Pratt	1991	GB	SS	DOT	L 5	+	0	50	20	40
				DOT	L 5	+	0	65	20	40
				DOT	L 10	+	0	50	20	40
				DOT	L 10	+	0	65	20	40
Pratt	1993	GB	Pine	DOT+Urea	L 4	_	45	100	15	14
				Sod.decabor.	L 4	_	0	100	15	14
Pratt	1994	GB	SS	DOT	L 0.5	+	100	100	20	46
				DOT	L 1	+	95	100	20	46
				DOT	L 2	+	75	100	20	46
				DOT	L 4	+	45	100	20	46
Pratt	1994	GB	SS	DOT	L 1.5	+	47	64	180	50
				DOT	L 3	+	21	64	180	50
Rishbeth	1959	GB	Pine	DOT	L 20	+	0	100	30	16
	1967			DOT	L 20	_	6	10	?	250
Weir	1969	Can.	WH	DOT	L 15	+	0	75	20	26
			DF	DOT	L 15	+	20	85	20	26

Notes:

(Dam)[a] = stumps damaged after treatment
(Del)[b] = treatment delayed

Date Year of publication (see bibliography)

Spp. WH = western hemlock, DF = Douglas fir, Fir = *Abies* spp., NS = Norway spruce, SS = Sitka spruce

Material DOT = disodium octaborate tetrahydrate
EA35 = 36% ethyl alcohol
Glyc = glycerol-alcohol
Sug = 10% sucrose
DOT+Urea = 4% DOT and 37% Urea
Sod. decabor. = sodium pentaborate (disodium decaborate decahydrate)

Form L = liquid, P = powder

Conc. % Concentration (usually w/v%)

Inoc. += artificially inoculated with spores, – = not inoculated

%T Incidence (%) of infected, treated stumps

%C Incidence (%) of infected, untreated control stumps

Reps. Experimental treatment replications (numbers of stumps)

Weeks Duration of trial

Table 3. Number of experiments by location and host species

	Pines	*Non-pines*[a]	*Total*
N. America	22	27	49
Britain	16	17	33
Europe	2	1	3
Total	40	45	85

[a] Non-pines include spruces, firs and larches

Table 4. Frequency of use of different borates, by host species

	Pines	*Non-pines*	*Total*
Borax	20	27	47
DOT[a]	17	18	35
Other borates	3	0	3
Total	40	45	85

[a] DOT = disodium octaborate tetrahydrate

Table 5. Mean percentage incidence of stump infection by *H. annosum* in experiments in which all forms of borate were used, by host species

		Mean incidence (%) of infection:	
	No. of experiments	*Treated stumps*	*Untreated stumps*
Pine	40	6	53
Non-pine	45	19	62

Table 6. Mean percentage incidence of stump infection by *H. annosum* in 82 experiments in which borax or disodium octaborate were used

			Mean incidence (%) of infection:	
	Formulation	*No. of experiments*	*Treated stumps*	*Untreated stumps*
Borax	Powder	22	10	60
	Liquid	25	9	62
Disodium octaborate	Powder	1	21	80
	Liquid	34	19	52

Table 7. Mean percentage incidence of stump infection by *H. annosum* in 59 experiments using liquid borates at various concentrations

Substance	*Concentration (%)*	*No. of experiments*	*Mean incidence (%) of infection: Treated stumps*	*Untreated stumps*
Borax	<5	1	0	26
	10	23	10	66
	<11	1	0	No data
Disodium octaborate	<5	7	55	77
	5	12	13	44
	10	11	7	41
	>10	4	6	68

(1980), who observed a ten-fold reduction in the number of diseased *Pinus elliottii* (Englm.) adjacent to stumps that had been treated with dry borax three years earlier compared to untreated stumps.

Edmonds *et al.* (1989) assessed the severity of decay in stands of western hemlock 20 years after they were thinned and treated with borax or left untreated, and found no significant difference in incidence of decayed trees in plots that had or had not been treated. In the south-eastern United States, experimental plots of three pine species (*P. strobus* (L.), *P. taeda* and *P. elliottii*) where borax had been applied in thinnings in 1969/70 were assessed for radial increment growth in 1988 (Tainter *et al.*, 1989). Mean radial increments calculated for the ten trees closest to the centre of each plot were not significantly different, and no effect of borax treatment was detected. In California, the influence of borax stump treatment in commercial fellings in natural pine stands was examined by a survey of stumps in two untreated and six treated crops, five to eleven years after cutting (Kliejunas, 1989). Incidence of stumps with sporophores of *H. annosum* in crops treated with borax was nil to 4%, while in the untreated crops it was between 23% and 70%. The author suggested that the minimum size of a stump requiring treatment in this area should be increased from 15 cm to 41 cm, except where machine-shearing cut stumps flush with the ground and thus insulated them against the lethal high temperatures that develop within high-cut stumps of smaller diameter.

Efficacy trials in the UK

In their trials, Phillips and Greig (1970) included disodium octaborate along with several other chemicals, and applied it to Scots pine and to Sitka spruce stumps in 5% and 10% aqueous solutions immediately after felling. All stumps were then inoculated with basidiospores of *H. annosum*. In addition to this treatment, application of the chemical was delayed eight hours, or was made to stumps that were subsequently damaged. The results were equivocal, with the most successful treatment being on pine and at the higher concentration. In Sitka spruce, the incidence of infection in untreated, control stumps was so low that the efficacy of the substance was difficult to gauge. However, Seaby (1973) obtained good control in Sitka spruce in Northern Ireland using dry Fertiliser Borate 46 (a crude pentahydrate sodium tetraborate containing unrefined ore), applied at a rate equivalent to approximately 30 g B per m^2 of stump surface. He estimated that the concentration of borate applied was 19 times greater than the loading reported by Koenigs (1969) as needed to inhibit the germination of conidia of *H. annosum*. Addition of powdered dye to the borax provided evidence that the latter had gone into solution on the stump top and had not blown away.

Concern over the efficacy of urea (which is the currently used stump treatment chemical) prompted research into the effectiveness of disodium octaborate by the Forestry Commission, starting in 1990. The first trial was carried out in Scotland and Wales. Stumps of Sitka spruce were treated soon after felling with disodium octaborate at 5% or 10% concentration. Twenty-four hours later, they were inoculated with basidiospores of *H. annosum* in water. When sampled after about eight months, none of the 80 disodium octaborate-treated stumps had become infected, compared to 23 of the 40 inoculated, untreated control stumps and 47 of the 80 urea-treated stumps (Pratt, 1994).

In the second experiment (Pratt and Quill, in prep.), Sitka spruce stumps were treated with disodium octaborate at one of several concentrations at or below 4% w/v, and were inoculated with basidiospores. After 10 months, the stumps were sampled and assessed for colonisation by *H. annosum* at 60 mm depth. The incidence of infection and the areas of stump colonised by the fungus depended on the concentration of disodium octaborate, being lowest at 4% (45% incidence, 0.3% area colonised; Table 8).

Although a degree of control was evident using disodium octaborate at 2%, it was not considered adequate. The possibility that artificial inoculation was resulting in too severe a test led to the third trial (Pratt, 1994) in which the effect of varying the dosage of spores was examined. The experiment, which was conducted on Sitka spruce was repeated six times at monthly intervals. Stumps were treated with disodium octaborate at 1.5% or at 3%. The results showed a response to the spore dose in which some control of infection was evident in stumps treated with disodium octaborate at a concentration as low as 1.5%.

Borate, in the form of sodium pentaborate, and disodium octaborate (in mixture with urea), both as 4% aqueous solutions, were tested in harvesting machines on pine stumps in Thetford Chase (Pratt, 1993). The stumps were sampled within three months of treatment. All three stump treatment chemicals reduced the areas infected compared to controls. The application of stump treatment was uneven, and where it was inadequate (as evidenced by a lack of dye), infection by *H. annosum* was common. Boron levels were low in those parts of stumps where infection had occurred compared with the uninfected parts (3 ppm and 14 ppm maximum respectively).

Conclusions

The use of borates for the control of *Heterobasidion annosum* was reviewed from published and from anecdotal sources. The two most commonly used borates have been sodium tetraborate decahydrate (borax) and disodium octaborate tetrahydrate, the former as a powder as well as in aqueous solution and the latter in aqueous solution. Both have proved effective on stumps of many different conifer species throughout a wide range of sites, especially in North America.

Table 8. Effect of various concentrations of disodium octaborate on the amount of *H. annosum* in the sapwood and the heartwood of Sitka spruce stumps 10 months after inoculation with basidiospores of *H. annosum*

Disodium octaborate concentration (%)	*Number of stumps[a] with* H. annosum *infection*		*Average[b] suface area (cm²) colonised by* H. annosum		*Average[b] % surface area colonised by* H. annosum	
	Sapwood	*Heartwood*	*Sapwood*	*Heartwood*	*Sapwood*	*Heartwood*
4	0	9	0.00	0.3	0.0	0.3
2	1	15	0.08	5.0	0.1	5.8
1	3	19	6.4	17.8	3.1	17.2
0.5	5	20	10.4	16.8	8.4	14.3
0	2	20	5.1	19.6	3.7	22.1
SED (Av)			9.53	5.50		

[a] Out of 20

[b] Average of infected stumps

The evidence collected from this review suggests that control of *H. annosum* by borates is generally better on pine than on other conifers. This may be a reflection of the fact that pine is grown in areas where rainfall is comparatively low and that, in consequence, high loadings of boron can be achieved in stumps by the application of powdered borates. Certainly, there appears to be poorer efficacy of borates on less resinous species and in the areas of high rainfall. When used as liquids, the results of 59 separate trials demonstrate that the degree of control achieved is related to concentration, which in the case of disodium octaborate should not drop much below 5%.

The review failed to find any research into the possible modes of action of the borates as stump protectants more recent than that which was published 20 years ago. Whether inferences can be drawn from the increasing literature on the mode of action of borates as wood preservatives is not yet clear.

Stump treatment by harvesting machine inevitably results in the spraying of the treatment material on the ground as well as on the stump itself, and this raises concerns of environmental pollution. The amounts of boron that are misdirected have not been measured, but it is unlikely that as much would be sprayed on forest land as is commonly applied as arable fertiliser. An additional consideration is that the chemical is applied locally rather than as a blanket cover, and that much of it is effectively locked-up in the woody stump tissues.

There is much literature on the tolerance of some plant species to boron, especially relating to deficiencies in crops that can be rectified by application of fertiliser. Data on phytotoxicity are less common, and tend to refer to arid areas or industrial sites: there are few references from Europe as a whole, and none on the susceptibility of indigenous British flora. Thus, some extrapolation from data published elsewhere would be needed to assess the threat posed to our flora from stump treatment. This may prove difficult without empirical tests because of the extremely wide tolerance exhibited by different plant species to boron, and because of the wide range of climatic and edaphic features in Britain. The risk to plants on clay soils, on soils with high pH, and on humus-rich soils would seem to be lower than to plants on poorly buffered, coarse-textured freely drained soils. Another problem in assessing the risk of phytotoxicity to forest plants from data derived from arable crops is that, in the latter, phytotoxicity is recognised as that which reduces crop yield. This is a criterion of limited relevance where the important factor may be the conservation of a wild plant.

Part of the concern about phytotoxicity in Britain arises from the use of borates as non-selective weedkillers in the 1960s. However, application rates of 20-100 kg boron per ha were recommended to kill annual weeds, rates far in excess of those that would normally be applied in stump treatment by tree harvester, which are not expected to exceed 4 kg per ha.

Evidence from the reports quoted in this review suggests that boron is not persistent in soil, especially in non-arid areas, and that application of some boron to the soil surface will not usually result in long-term contamination.

The lack of data on the toxicity of boron to aquatic organisms is perhaps less important, because maximum concentrations that have been agreed for boron in freshwater were not exceeded in the stump-treatment trial of disodium octaborate undertaken by the Forestry Commission in 1994. Data on mammalian toxicity of borates are numerous, largely because of the wide range of domestic and industrial uses that borates have been put to for the past 100 years. A recent symposium (Anon., 1992) has not changed the assessment that, properly used, borates are unlikely to be harmful to man.

The conclusion of this review is that borates are effective at controlling *H. annosum* infection of stumps under most circumstances, and that their use in Britain would have little risk of consequential damage to plants, animals or man.

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