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Poplar for the phytomanagement of boron contaminated sites

B.H. Robinson [a,*], S.R. Green [b], B. Chancerel [b], T.M. Mills [b], B.E. Clothier [b]

[a] Institute of Terrestrial Ecosystems, Swiss Federal Institute of Technology (ETH), Universitätstrasse 16, CH-8092 Zürich, Switzerland
[b] HortResearch, Private Bag 11030, Palmerston North, New Zealand

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Poplars reduce boron leaching from contaminated sites.

Abstract

Boron (B) is a widespread environmental contaminant that is mobile relative to other trace elements. We investigated the potential of hybrid poplar (*Populus* sp.) for B phytomanagement using a lysimeter experiment and a field trial on B-contaminated wood-waste. In both studies, poplars enhanced evapotranspiration from the wood-waste, reduced B leaching, and accumulated B in the aerial portions of the tree. When grown in a substrate containing 30 mg/kg B, poplar leaves had an average B concentration of 845 mg/kg, while the stems contained 21 mg/kg B. Leaf B concentrations increased linearly with leaf age. A decomposition experiment revealed that abscised leaves released 14% of their B during the winter months. Fertiliser application enhanced tree growth without decreasing the leaf B concentrations. Harvesting alternate rows of trees on a contaminated site would reduce leaching from the site while removing B. Harvested plant material may provide bioenergy, stock fodder, or an amendment for B-deficient soils.

Keywords: Phyto-DSS; Phytoremediation; Boron; Biofuel

1. Introduction

Phytomanagement is the use of vegetation/soil amendment systems to reduce the environmental risk posed by contaminated sites (Bañuelos, 1995).

Poplars are often planted to reduce the water flux through contaminated sites because of their ease of propagation, rapid establishment, deep roots, and ability to coppice (Mills and Robinson, 2003). Poplars thrive in a wide range of soil and climatic conditions (McGee et al., 1981). Bañuelos et al. (1999) reported that when irrigated with water containing 3 mg/L B, some poplar clones accumulated up to 543 mg/kg of B in their aerial tissues. Subsequently, we found that when grown in soil containing just 40 mg/kg B, poplars accumulated up to 1200 mg/kg in the leaves, some 20 times more than other species grown in the same environment (Robinson et al., 2003a).

The high evapotranspiration of poplars combined with their high B uptake may reduce the environmental risk arising from B-contaminated sites. Poplars may reduce B leaching into ground and surface waters by returning rainfall to the atmosphere via evapotranspiration and by binding B in the plant tissue. Harvesting the trees would remove B from the site (Robinson et al., 2003a).

1.1. Boron as an environmental contaminant

Boron (B) generally occurs only in small concentrations in soils, but has a disproportionately large impact on plants, both as an essential element and as a toxin. High levels of B occur naturally in soils in arid areas.

Boron contamination results from a wide range of anthropogenic activities. Although most B (76%) is used in the manufacture of glass (Parks and Edwards, 2005), B in borosilicate

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* Corresponding author.
E-mail addresses: brett.robinson@env.ethz.ch (B.H. Robinson), bclothier@hortresearch.co.nz (B.E. Clothier).

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glass is essentially immobile and thus poses little environmental threat. However, other uses of B that depend on its bleaching or antiseptic properties may result in the release of mobile B into the environment (Nable et al., 1997). Boron timber treatment reduces flammability, prevents sap-stain, and protects against insect damage. Sites associated with the timber-industry may therefore have high B concentrations.

High B concentrations occur in some industrial byproducts. Boron is one of the most important contaminants in most coal-ash materials (Adriano, 2001). It has been estimated that annually 11 800 t of B are released in coal fly ash from coal combustion (Bertine and Goldberg, 1971). Boron is the most mobile element when coal-ash is buried (Doak, 2003). Water-soluble B varies from 17 to 64% of the total B present in a range of fly ashes (James et al., 1982).

1.2. Boron mobility in soil

Boron is relatively mobile in soil when compared to metal contaminants. Boron binds to kaolinite and illite clays, as well as sewage sludge, with a maximum sorption density of just 31 mg/kg B (Banerji, 1969). Su and Suarez (1995) showed that B forms inner-sphere complexes with some minerals, including Al and Fe hydroxides, allophane, and kaolinite. However, quartz and calcite adsorbed negligible amounts of B from solution. Soil organic matter absorbs much of the total B. Microbial action can remobilize organic-bound B (Evans and Sparks, 1983).Goldberg (1997) showed that the Langmuir and Freundlich equations described the adsorption of B in soil.

1.3. The toxicity of B in soils and waters

In plants, the range between B deficiency and toxicity is smaller than for any other element (Goldberg, 1997). Boron has four modes of toxicity in higher plants: (1) disruption of cell wall development; (2) metabolic disruption by binding to ATP, NADH or NADPH; (3) disruption of cell division and development by binding to RNA; and (4) osmotic imbalances caused by high B concentrations in leaves (Reid et al., 2004). Species differ in their tolerance to B. Sensitive species succumb when irrigated with just 0.3 mg/L B, while tolerant species resist up to 4 mg/L B in irrigation water (Keren and Bingham, 1985).

Toxicity in animals occurs when intake exceeds the rate of excretion. A 2003 U.S. Environmental Protection Agency (EPA) Drinking Water Health Advisory for B recommends a maximum safe lifetime in drinking water of 0.6 mg/L B (US EPA, 2003).

1.4. Mechanisms of B uptake by plants

The neutral species $B(OH)_3$ is taken up more readily than $B(OH)_4^-$. This is because $B(OH)_4^-$ is more strongly bound to clay minerals (Hu and Brown, 1997) and because roots take up $B(OH)_3$ more readily than $B(OH)_4^-$ from soil solution. Oertli and Grgurevic (1975) found that barley roots accumulated more $B(OH)_3$ than $B(OH)_4^-$ in solution culture. Soil pH is the most important factor in controlling B uptake (Gupta, 1979). Plant uptake is reduced at higher soil pH values because of the increasing ratio of $B(OH)_4^-:B(OH)_3$. Therefore, liming reduces the availability of B to plants (Gupta and Macleod, 1981; Berger and Truog, 1945; Peterson and Newman, 1976). While there is unanimous agreement that B is translocated in xylem to sites of greatest water loss, there is controversy regarding the role of the phloem in providing B to sites that do not lose water readily (Brown and Shelp, 1997).

1.5. The phytomanagement of B-contaminated sites: aims

Successful phytomanagement of B should reduce the negative effect of this element on the surrounding environment. Vegetation should be established that reduces water flux through the site or reduces the concentration of dissolved B in the leachate. Both these effects result in a lower B concentration in ground and surface waters. To achieve this, any phytomanagement strategy must increase evapotranspiration from the site and/or remove B from soil solution, either by plant uptake or by altering the speciation of B in the soil.

The uptake of B into the aerial portions of poplar does not represent the same environmental risk as the uptake of some other trace elements, such as Cd. This is because B is not biomagnified through the food chain (Howe, 1998) since it is readily excreted by animals.

We aimed to determine the suitability of poplar for the phytomanagement of a B-contaminated wood-waste site and investigate the effect of various management strategies on the leaching and plant uptake of B. Specifically, we sought to determine: (1) the B uptake characteristics of poplar, namely the extent and distribution of B in the aerial portions, and how B concentration changes as a function of time; (2) the effect of plant nutrients on B uptake; (3) the release of B from decomposing poplar leaves; and (4) model the effects of poplars on B leaching from a contaminated site.

2. Materials and methods

2.1. Site description

The Kopu wood-waste site is located at the base of the Coromandel Peninsula, North Island, New Zealand (37.2° S, 175.6° E). The site has a surface area of 3.6 ha. Over a 30-year period, from 1966, timber-processing operations dumped wood-waste and yard-scrapings, resulting in a pile with an average depth of 15 m. Surrounding land was engineered so that no ground or surface water entered the pile, and leachate resulting from rainfall was collected in a small holding pond at the foot of the pile. Vegetation had failed to establish and evaporation from the surface of the pile was negligible, even in the summer months. There was saturated material at depths as shallow as 20 mm.

Leachate resulting from the annual rainfall of 1135 mm, as measured at a nearby meteorological station at Thames, regularly caused the holding pond to overflow and enter a local stream. This overflow elevated B concentrations in the stream to levels that were in excess of 1.4 mg/L, the New Zealand Drinking Water Standard (NZDWS), especially in the summer months when stream flow was low. In response to these breaches, the local environmental authority placed an order on the forestry company responsible for the site that the problem be remedied (Robinson et al., 2003a).

2.2. Poplar plantings

In July 2000, a test planting was established on the Kopu site using clones of poplar and willow hybrids, namely *Populus deltoides* × *nigra* ('Argyle' & 'Selwin'), *P. deltoides* × *yunnanensis* ('Kawa'), *Populus euramericana* × *yunnanensis* ('Toa'), *Populus alba* × *glandulosa* ('Yeogi'), *P. nigra* × *manimowic* ('Shinsei'), *Salix matsudana* × *alba* ('Tangoio'), *Salix kinuyanagi*, and *Salix purpurea*. The planting also included *Eucalyptus fastigata* and *Eucalyptus nitens*. We planted at least three 100 m rows of each clone/species at an average spacing of approximately 1.5 m between the trees. We arranged the rows sequentially, forming three blocks each containing one row of each clone/species. Additional rows and other plantings occurred along the margins, particularly at the foot of the pile.

The following year, the remainder of the site was planted with *P. deltoides* × *yunnanensis* ('Kawa') and *P. alba* × *glandulosa* ('Yeogi') in randomly arranged rows at a density of 7000 trees/ha. The trees were fertilised annually with Nitrophoska Blue (N–P–K 12–5–14, Kali and Salz, Germany), applied either manually or using a helicopter at a rate of ca. 100 g/m^2. A pump, installed near the holding pond at the foot of the pile, irrigated the trees during the summer months.

In April of 2001, 2002 and 2003, we measured the heights of each individual tree of 'Toa', 'Kawa' and 'Yeogi' using a graduated height stick. For each poplar clone, we selected three specimens representing the 25th, 50th, and 75th percentile for tree height. Destructive harvesting of the trees permitted the determination of the dry biomass of the stems and leaves. At the end of the second growing season, in April 2002, we sampled seven Kawa, six Toa and eight Yeogi at regular locations over the pile for chemical analyses. For each tree, we abscised one lateral branch and separated the stems and leaves. We sampled the substrate from the root-zone of each tree at a depth of approximately 50 mm, after the removal of any surface leaf litter.

2.3. Parallel lysimeter experiment

A parallel lysimeter experiment was performed in a shade-house at HortResearch, Palmerston North, New Zealand. Fig. 1A shows the cumulative potential evapotranspiration for the duration of the experiment. Seven thousand litres of wood-waste from the aforementioned Kopu site were homogenised using an earth-moving machine. Initially, the wood-waste contained total B, Cu, Cr and As concentrations of 39.9, 140, 15 and 6.3 mg/kg, respectively. The bulk density of the wood-waste was 0.23 with a water-holding capacity of 420 mL/kg, and a pH of 4.7. In October 2000, we filled eight 800-L weighing lysimeters with the wood-waste, and planted a 1 m long poplar pole of the clone 'Toa' (*P. euramericana* × *P. yunnanensis*) in each. The lysimeters were

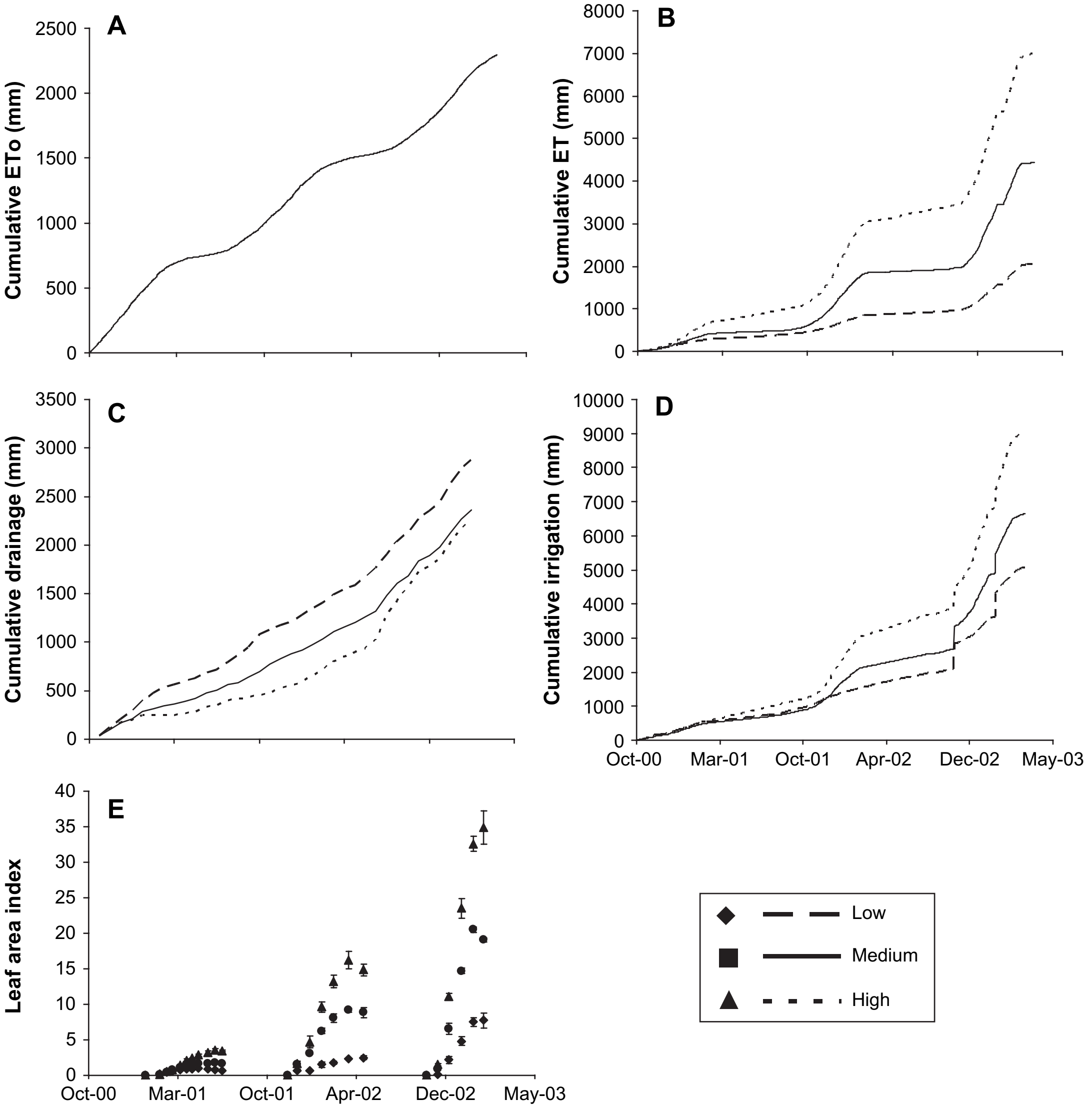

Fig. 1. Factors affecting the water balance. Lines represent the average cumulative values for the low, medium, and high fertiliser treatments. (A) Potential evapotranspiration (ETo), (B) measured evapotranspiration (ET), (C) drainage, (D) irrigation, and (E) leaf area index. Note that the surface area of the lysimeters was 0.63 m^2.

fertilised with Hoagland's solution (Hoagland and Arnon, 1950) at three concentrations: low (two lysimeters), medium (three lysimeters) and high (three lysimeters). Fertilisation occurred annually from March to September. The total N–P–K applied to each lysimeter was (in grams, respectively): low 45–7–50, medium 90–14–99, and high 135–20–149. Hoagland's solution also contains B. Table 3 shows the B mass balance. We used these plant-nutrient treatments to determine the effect of substrate fertility on plant water use and foliar trace element concentrations.

The lysimeters were given a measured amount of water daily to maintain their volumetric water content between 0.50 and 0.60 m^3/m^3. Fig. 1D shows the cumulative irrigation applied to the 'low', 'medium', and 'high' treatments. We collected the drainage weekly and weighed it. Every 2 weeks we removed every 10th leaf, counting from the oldest leaf on the first shoot, through to the youngest leaf before the apical bud. The leaves were then dried, ground and stored for analysis. In mid April of 2001, 2002 and 2003, we removed all the leaves from the trees and measured their total dry biomass. In May 2003, we divided the wood-waste in the lysimeters horizontally into 0.2 m portions, taking three samples from each depth portion, and ensuring each sample was free of roots. We did not sample the roots and stems of the poplars.

2.4. Boron leaching from abscised leaves

We conducted an experiment to determine the rate of B leaching from poplar leaves during the winter months, under controlled conditions. This experiment used leaves from the final harvest of the lysimeter experiment. In May 2003, we filled three cylinders, each 0.5 m long and 0.39 m in diameter, with 5 kg of fresh leaf material (1.6 kg dry matter). The initial height of the leaves was 0.3 m, decreasing to 0.13 m at the end of the experiment. We covered the bottoms of the cylinders with plastic gauze and placed the cylinder upon a collection bucket. The cylinders were irrigated daily with 0.1 L of water. We collected the drainage every week, which on average was 42% of the volume irrigated. After 14 weeks, the leaf material was dried, weighed, and analysed for B along with the acidified leachate samples.

2.5. Sample preparation and elemental determination

Samples were analysed for B at certified commercial laboratory (Hill Laboratories, Hamilton, New Zealand) using the US EPA Method 200.2 (US EPA, 1994) for total recoverable trace elements. The digestion uses nitric and hydrochloric acids to dissolve sieved or ground material. Digests were analysed using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES).

3. Results and discussion

3.1. Poplar growth and B uptake at the Kopu site

A visual assessment in the autumn of 2002 revealed that only three of the 11 clones/species in the test planting provided any significant growth in the first year. These were *P. euramericana* × *yunnanensis* ('Toa'), *P. deltoides* × *yunnanensis* ('Kawa'), and *P. alba* × *glandulosa* ('Yeogi'). By the second growing season, many of the other clones/species had perished. Table 1 shows the stem and leaf biomass production for the selected poplar clones during the first 3 years of growth. The biomass of all three species increased exponentially during the measurement period. By the end of the 2002–2003 growing season, the approximate dry biomass of the trees cover on the Kopu site was over 30 t/ha. This is comparable to the biomass production of poplars growing in a similar environment on non-contaminated soil (Pilar Ciria, 1999).

Table 2 shows the B concentrations in the stems and leaves of 2-year-old poplars at Kopu, along with the B concentration of the wood-waste in which they were growing. All three clones accumulated B to concentrations greater than 700 mg/kg on a dry matter basis, some 25 times greater than the B concentration in the wood-waste where they were growing. There were no significant differences in B uptake between the three clones. For all clones, there were significant and positive correlations between the leaf and wood-waste B concentrations. In contrast to the leaves, the stems had lower B concentrations than the wood-waste in which the trees were growing.

Poplar growth at the Kopu site changed the physical and biological properties of the wood-waste. After 3 years' of growth, wood-waste in the root-zone became a dark humus-like material, which was colonised by worms and other organisms. We did not quantify these changes.

3.2. Poplar growth and B uptake in lysimeters

Table 1 shows the annual leaf biomass production of the poplars in the lysimeter experiment. Biomass significantly increased upon the addition of fertiliser. Compared to the trees in the lysimeter experiment, the growth of the trees at Kopu was between the "low" and "medium" fertiliser treatments. The trees grown in the 'low' fertilisation treatment showed visible signs of nutrient deficiency, namely stunting and chlorosis.

Table 3 shows the water balance for the three treatments throughout the experiment. There was, at most, a 4% discrepancy between the water added to the system and the water lost from the system. Fig. 1(A–E) shows the data affecting the tree's water use during the experiment. As expected, the

Table 1
Average biomass production (kg) of individual poplar trees from the field site at Kopu and from the parallel lysimeter experiment

		2000–2001		2001–2002		2002–2003	
		Leaf	Stem	Leaf	Stem	Leaf	Stem
Kopu field site	Variety						
	Kawa ($n = 3$)	0.12 (0.01)	0.10 (0.01)	0.41 (0.12)	1.03 (0.32)	0.85 (0.18)	3.40 (0.86)
	Toa ($n = 3$)	0.06 (0.00)	0.11 (0.01)	0.53 (0.07)	1.31 (0.25)	0.80 (0.12)	3.52 (0.64)
	Yeogi ($n = 3$)	0.11 (0.00)	0.12 (0.00)	0.50 (0.03)	2.69 (0.36)	0.98 (0.22)	5.27 (1.28)
Parallel lysimeter experiment	Treatment						
	Low ($n = 2$)	0.09 (0.01)	nd	0.36 (0.00)	nd	0.67 (0.06)	nd
	Medium ($n = 3$)	0.19 (0.00)	nd	0.88 (0.03)	nd	1.49 (0.08)	nd
	High ($n = 3$)	0.32 (0.03)	nd	1.45 (0.12)	nd	2.08 (0.01)	nd

The variety used in the lysimeter experiment was Toa. Values in brackets are the standard error of the mean. nd, Not determined.

Table 2
Average total B concentrations (mg/kg) in the wood-waste and in 2-year-old poplar trees at Kopu

Clone	Wood-waste	Stem	Leaf	Gradient	Correlation r (p)
Kawa ($n = 7$)	31 (7)	20 (5)	827 (166)	25.6	0.76 ($0.05 > p > 0.01$)
Toa ($n = 6$)	36 (9)	22 (4)	1012 (103)	24.4	0.87 ($0.05 > p > 0.01$)
Yeogi ($n = 8$)	28 (5)	20 (1)	776 (97)	26.4	0.87 ($0.01 > p > 0.001$)
Average of all trees ($n = 21$)	30 (4)	21 (2)	845 (71)	25.4	0.74 ($p < 0.001$)

The gradient and correlation, respectively, describe the slope of the leaf [B]/wood-waste [B] regression line, and the fit of this line to the data. Values in brackets are the standard error of the mean.

high biomass production of the higher fertiliser treatments translated into a greater leaf area index (Fig. 1E). For the medium and high treatments, the leaf area index exceeded the value of six, at which maximum transpiration occurs in a poplar forest under high light conditions (Heilman et al., 1996). The cumulative evaporation increased upon fertiliser treatment (Fig. 1B). There was significantly less drainage from the 'medium' and 'high' fertiliser treatments compared to the 'low' treatment (Fig. 1C), despite the maintenance of all the lysimeters at similar water contents throughout the experiment.

The evapotranspiration in the lysimeter experiment does not correspond to the field situation. The trees in the lysimeters received significantly more light than those at Kopu because there were no adjacent trees that blocked sunlight. The average crop coefficient, defined as the actual evapotranspiration (Fig. 1B) divided by the potential evapotranspiration (Fig. 1A), during our lysimeter experiment was 0.9, 1.9 and 3.1 for the low, medium and high treatments. Poplars in the field have a maximum crop coefficient ($K_{c(\max)}$) of 1.0 (AgriMet, 2006). Therefore, in the field situation, fertiliser addition will increase the speed of plant establishment and decrease the time from planting to $K_{c(\max)}$, but not significantly increase tree water use from the site under closed-canopy conditions.

Table 3 shows the mass balance for B in the lysimeter experiment. The amount leached was four times more than the amount added with the Hoagland's solution in the 'high' treatment. This indicates that the wood-waste B concentration decreased during the experiment and that the B in the Hoagland's solution was unlikely to have significantly enhanced plant B uptake. During the 3-year experiment, the poplars extracted into their leaves 21, 30, and 42% of the initial wood-waste B for the 'low', 'medium', and 'high' treatments, respectively. Although the drainage regimes were not comparable across the 3 years, the concentration of B in the drainage water in the last year was, on average 0.23 mg/L, a value lower than the Australia New Zealand Environmental Conservation Council's (ANZECC, 2000) threshold for B's Environmental Investigation Level. This third year level was just 10% of the initial leachate levels of 2.2 mg/L (Robinson et al., 2003a).

At the end of the experiment, there was a significant decrease in the wood-waste B concentration as a function of depth (Fig. 4). This is the opposite pattern of what one would expect if leaching occurred in a homogeneous lysimeter. Capillary rise could increase surface B concentrations. However, this is unlikely because we irrigated the lysimeters to excess to produce drainage. Another explanation may be that most of the roots occurred at depth and thus removed more B from the bottom of the wood-waste profile that the top. We observed, but did not quantify, that most of the roots were at the bottom of the lysimeters. Unfortunately, we had no lysimeters without trees, so the effect of the roots on the B distribution in the wood-waste remains unclear.

The amount of B that leached from the lysimeters significantly decreased as the rate of fertilisation increased (Fig. 2). Since the leaching volumes of the 'medium' and 'high' fertiliser treatments were not significantly different, the lower amount of B that leached from the 'high' treatment

Table 3
Mass balance of B and water in the lysimeters, from the initial planting in October 2000 to the end of the experiment in May 2003

	Low ($n = 2$)		Medium ($n = 3$)		High ($n = 3$)	
	Boron (g)	Water (m^3)	Boron (g)	Water (m^3)	Boron (g)	Water (m^3)
Initial						
Wood-waste	4.438 (0.002)	0.661 (0.000)	4.252 (0.008)	0.627 (0.007)	4.268 (0.219)	0.636 (0.019)
Added	0.108	3.222 (0.251)	0.216	4.220 (0.175)	0.320	5.740 (0.330)
Total	4.546	3.883	4.468	4.847	4.588	6.376
Final						
ET	–	1.304 (0.133)	–	2.809 (0.119)	–	4.446 (0.414)
Leaves	0.859 (0.042)	0.002	1.173 (0.199)	0.005	1.972 (0.092)	0.007
Wood-waste	1.207 (0.301)	0.622 (0.006)	1.089 (0.076)	0.594 (0.010)	1.302 (0.011)	0.556 (0.013)
Drainage	2.019 (0.503)	1.826 (0.366)	1.596 (0.108)	1.500 (0.215)	1.329 (0.238)	1.434 (0.078)
Total	4.086	3.752	3.859	4.908	4.603	6.443

Values in brackets are the standard error of the mean. ET, Evapotranspiration.

was due to a decrease in the B concentration in the leachate. Thus, fertilisation improved the quality of the drainage water.

There were no significant differences in the leaf B concentrations between the different fertilisation regimes. This indicates that the macronutrient status of the tree did not affect the leaf B concentration. Nevertheless, the amount of B extracted per tree increased with increasing biomass production. Fig. 3 shows the average leaf B concentrations of all the trees throughout the experiment. Interestingly, there was no significant decrease in the leaf B concentration over the 3 years, despite a decrease in the substrate B concentration due to leaching and plant uptake. This may have been due to root development increasing the pool of plant-available B.

Within a single year, the leaf B concentrations were significantly and positively correlated with time. Thus, harvesting the trees at the end of the growing season before leaf fall would result in the highest rate of B removal from the site. This pattern of accumulation is consistent with the hypothesis that B transport occurs in the xylem and thus B accumulates in the leaves, which are a major water sink. Laureysens et al. (2004) observed a similar trend in the accumulation of other trace elements by European poplar varieties.

3.3. Assessing the fate of B from abscised leaves

Most of the B taken up by the poplars is stored in the leaves (Table 1), and therefore returned to the soil each autumn following leaf abscission. The rate of B leaching from the decomposing leaves will affect the B concentration in any drainage from the site. The B that the leaves release during the winter months is likely to leach from the site, as evapotranspiration is minimal at this time.

After 14 weeks of decomposition, the leaves in our experiment had lost 45% of their initial mass, yet only 14% of their initial B content (Table 4). The leaves retain most of the B during the winter months. The rate of decomposition in our experiment is likely to be greater than would occur on the Kopu site because the experiment occurred in a shade-house where the temperatures were a few degrees higher than the Kopu site.

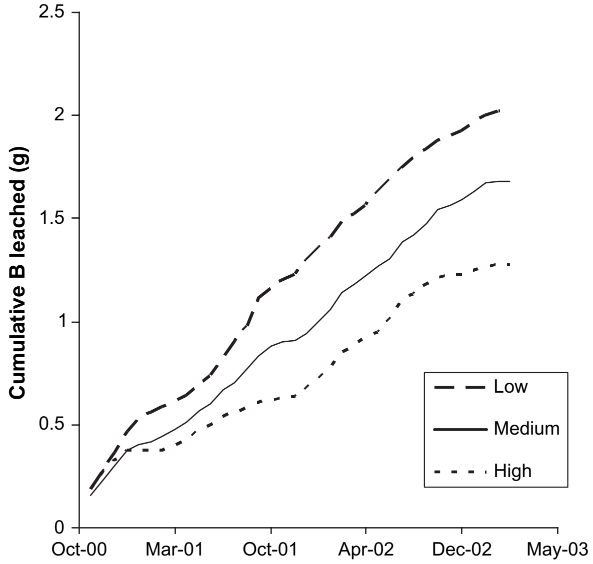

Fig. 2. Cumulative mass of B leached. The lines represent the average values for the low fertiliser ($n = 2$), medium fertiliser ($n = 3$) and high fertiliser ($n = 3$) treatments in the lysimeter experiment.

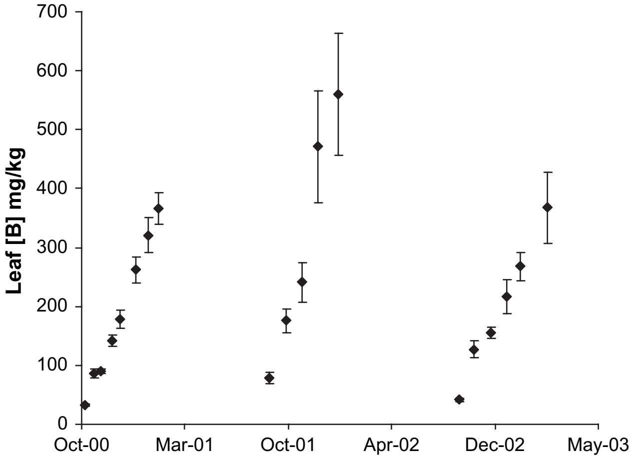

Fig. 3. Average leaf B concentrations for all trees in all treatments in the lysimeter experiment ($n = 8$). All data are averaged because there were no significant differences between treatments.

These results indicate that during the winter months, the contribution of B from leaves to the B loading in leachate from the Kopu site is negligible. Presumably, the rate of decomposition and B release will increase in the following summer. At this time, the released B is less likely to leach because evapotranspiration rates are at a maximum. Nevertheless, unless trees are periodically removed from the site, the total B loading of the site will remain constant.

4. The application of phytomanagement

The most important factor in using poplar for phytomanagement is the successful establishment of trees on the site. Our experiments revealed that just three clones could tolerate the environmental conditions on the Kopu site. We cannot attribute this result to poplar B-tolerance alone, since wood-waste is an exotic medium for poplar growth and may have other growth-limiting factors. Every contaminated site has unique environmental conditions; therefore, a planting trial to determine the most suitable species/clones is an essential component of phytomanagement. Planting more species/clones reduces the risk of

Table 4
Changes in average ($n = 3$) leaf B content and dry biomass after decomposition

Boron	Mass (g)	Percentage
Initial (leaves)	0.560	100
Final (leaves)	0.485 (0.010)	86 (1.7)
Final (leachate)	0.075 (0.005)	14 (0.9)
Leaf biomass	Mass (kg)	Percentage
Initial	1.6	100
Final	0.889 (0.071)	55 (5)

Values in brackets are the standard error of the mean.

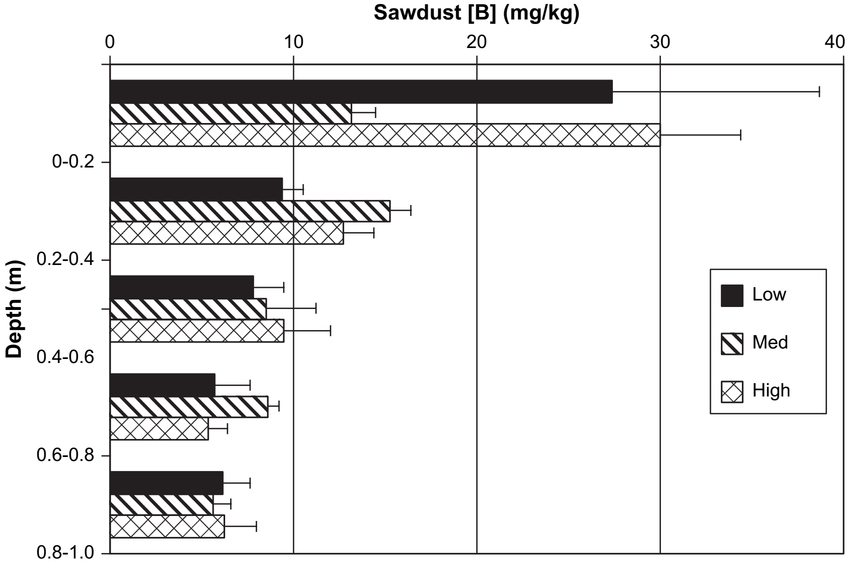

Fig. 4. The B distribution in the low fertiliser ($n = 2$), medium fertiliser ($n = 3$) and high fertiliser ($n = 3$) treatments in the lysimeter experiment at the end of the experiment in May 2003. Error bars represent the standard error of the mean.

a single pest, such as rust (*Melampsora* spp.), damaging the entire site. Fertiliser application enhances tree establishment and does not reduce the leaf B concentration.

The change in appearance in the wood-waste under the poplar trees and the increase in soil organisms such as worms may indicate increasing fertility. If so, then planting other species, such as the native grass Toetoe (*Cortaderia toetoe* Zotov.), would enhance the biodiversity of the site.

The establishment of poplar on a B-contaminated site can reduce, or eliminate, B leaching via evapotranspiration alone. At Kopu, the collection and re-irrigation of drainage water further reduces leaching because it allows the trees to transpire at a maximum for the entire growing season by annulling the effect of droughts. Re-irrigation also reduces the importance of preferential flow processes. Normally, preferential flow permits water and solutes to traverse the vadose zone without interacting with roots, thus increasing leaching. However, this effect is less at the Kopu site because re-irrigation can occur ad infinitum. Re-irrigation also allows the tree roots to interact with B that has originated below the root-zone, which would otherwise be unavailable for plant uptake.

In some cases, such as at Kopu, leaching is unavoidable because rainfall is greater than evapotranspiration. The holding pond at Kopu overflows at the end of winter and after exceptionally heavy rainfall. However, at these times the additional water carried in the local streams dilutes the B concentration in the leachate. Since at low concentrations, B is a beneficial micronutrient, dilution, in this case, is the solution to pollution.

4.1. Site maintenance

In addition to hydraulic control of leaching from B-contaminated sites, the uptake of B into the leaves further reduces leaching because the abscised leaves release B only slowly. Nevertheless, equilibrium will occur when the decaying leaves release B as fast as the poplars take it up.

Boron could be removed from contaminated sites by removing the leaves after abscission or by periodically removing the above-ground biomass of the trees (coppicing). Leaf removal would be optimal, since transpiration would occur apace in the following growing season. However, this method may be prohibitively expensive.

Poplar trees re-grow from stumps, eliminating the need for replanting. Results from our lysimeter experiments indicate that the optimal time to coppice is at the end of the growing season, just before leaf fall because the B contained therein is maximised. However, coppicing may also increase the likelihood of leaching, because of the time needed for the trees to re-grow and establish the leaf area that is required to maintain high transpiration. An intermediate strategy, involving a partial coppice, may remove a fraction of the total biomass, thus removing B while contemporaneously limiting leaching. The amount of material removed and the frequency of removal are critical success factors for any coppicing strategy.

Here we discuss the effects of various management strategies using computer model, the Phyto-DSS (Robinson et al., 2003a,b), to simulate the effect that various coppicing strategies will have on B removal and leaching from the Kopu site. We parameterised the model using results from our experiments at Kopu, along with meteorological data from Thames during the period 1990–2000. We calculated leaching from the site (Fig. 5A), as well as the initial rate of B removal (Fig. 5B), namely the amount of B removed in the first harvest. The simulated coppicing strategies examined here all begin after 3 years of growth, i.e. when the trees have established an extensive root system and can rapidly re-grow after coppicing. Removing 100% of the above-ground biomass annually would allow too much leaching, so we examined removing 25% and 50% of the above-ground biomass annually, as well as removing 25%, 50%, and 100% every 3 years.

These calculations indicate that annually removing 50% of the biomass after an initial 3 years of growth would only

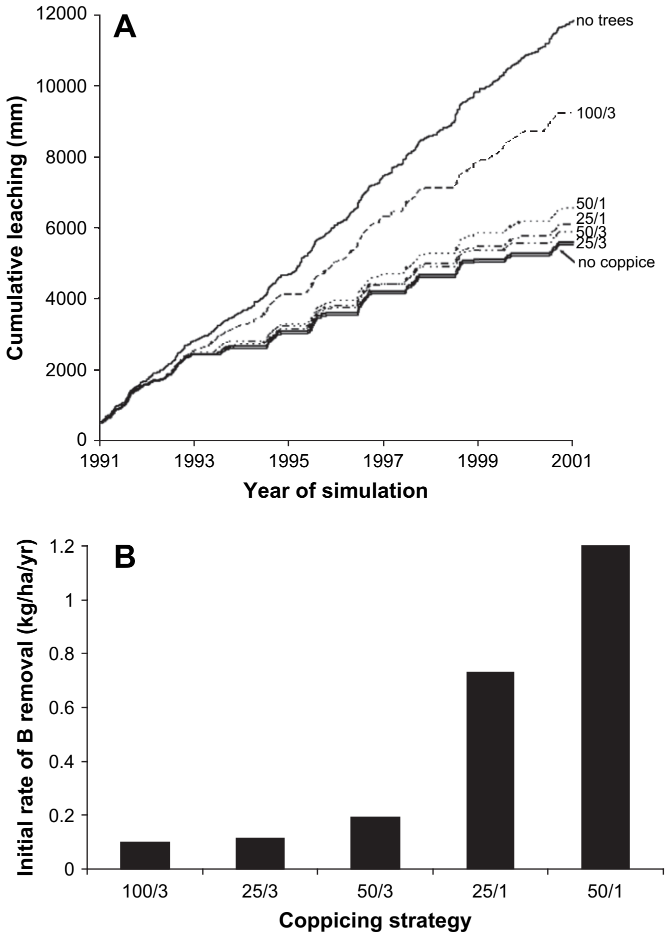

Fig. 5. (A) Simulations of various coppicing strategies on the cumulative leaching from the Kopu site. The first number represents the percentage of biomass removed, while the second denotes the frequency of removal, e.g. 100/3 means 100% of the biomass is removed every 3 years. Note that these simulations assume that there is no coppicing for the first 3 years. (B) The initial rate of B removal of the coppicing strategies shown in (A).

slightly increase the leaching from the site, while initially removing over 1 kg of leachable B per hectare (Fig. 5A, B). Although it would take many years to remove all of the B from the root-zone, our lysimeter experiments demonstrated that coppicing could rapidly reduce the levels of B in root-zone leaching. These calculations assume that pathogens, such as ‘silver leaf’ (*Chondrostereum purpureum*), do not affect the growth of the potentially B-stressed trees.

At the Kopu site, coppicing the trees may be essential to maintain a viable vegetative cover. Wood-waste is a low strength medium. Letting the trees grow beyond a certain height may increase the likelihood of them toppling over.

4.2. Use of B-rich biomass following B phytoextraction

The poplars growing on the Kopu site had a high B concentration relative to pasture species (Underwood and Suttle, 1999). Provided the leaves do not contain excessive amounts of other environmental contaminants, the biomass may provide a source of this element to animal stock (Robinson et al., 2005), which depending on its concentration, may have beneficial effects such as increased growth and bone density (Mastromatteo and Sullivan, 1994). That B is an essential nutrient for mammals was unknown until recently, when researchers found that B plays a significant role as a cofactor for the hormones involved in mineral uptake into bone matrix structure, as well as the reproductive hormones oestrogen and testosterone (Nielsen et al., 1987).

Similarly, since B deficiencies are common in agricultural soils (Gupta, 1967), the harvested and mulched material may constitute an organic fertiliser on B-deficient soils. Here again, it is important that the leaves do not contain any additional contaminants that may have been present on the contaminated site.

Alternatively, the harvested material may provide biofuel. Here, the elemental composition of the trees is less important. Ash with a high B concentration could be stored in a sealed landfill or other place where it does not pose a risk to the environment. The use of poplar as biofuel relies on the presence of a nearby incinerator.

5. Conclusions

The phytomanagement of B using poplar is most effective when the trees are partially coppiced and where effluent from the site is re-irrigated onto the trees. Since each site has unique environmental conditions, whole-system mechanistic models are required to optimise the coppicing strategy. The high biomass production of the trees combined with their high leaf/soil concentration quotient may result in a significant decrease in the soil B in just a few years. Nevertheless, most polluted sites contain a suite of contaminants so removing the B will not result in site cleanup, just mitigate the effects of this highly mobile trace element.

A critical and unanswered question is the interaction of the roots with B-contaminated media. We do not know how much B is bound in the root system, nor do we understand how roots interact with B hotspots in heterogeneously contaminated media.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envpol.2007.01.017.

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