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THE WETLAND GRASS *GLYCERIA FLUITANS* FOR REVEGETATION OF METAL MINE TAILINGS

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Abstract: Revegetation under wetland rather than dryland conditions provides an alternative to traditional methods of rehabilitation of metal mine tailings. The wetland plant *Glyceria fluitans* (floating sweetgrass) was found growing in a lead/zinc mine-tailings pond. The potential of this species for revegetation of mine tailings under wetland conditions had not previously been investigated. In two outdoor experiments, *G. fluitans* of non-contaminated origin grew successfully on alkaline tailings containing elevated metal concentrations (230 μmol g^{-1} Zn, 11 μmol g^{-1} Pb). Growth of *G. fluitans* was significantly enhanced on tailings treated with NPK fertilizer (700 kg ha^{-1}), but the plants grew well even without fertilizer, indicating a low nutrient requirement. *Glyceria fluitans* did not survive on saline ($MgSO_4$) tailings originating from another mine that contained much higher lead (34 μmol g^{-1}) and iron (2584 μmol g^{-1}) concentrations. The ability of *G. fluitans* to tolerate many of the adverse conditions associated with mine tailings favors its use for revegetation purposes.

Key Words: mine tailings, revegetation, wetland cover, *Glyceria fluitans*

INTRODUCTION

Metal mine tailings, a waste product of the mining industry, are generally characterized by high metal concentrations and low nutrient contents. Coarse tailings generally have poor water-retention properties and high rates of evapotranspiration, whereas in finer tailings, there is often limited water infiltration (Bradshaw and Chadwick 1980, Hossner and Hons 1992). As a result of these features, tailings often remain unvegetated or very sparsely vegetated even long after mining operations have ceased. The lack of a vegetative cover means that tailings are often unstable and subject to wind erosion, which can lead to serious pollution problems (Bradshaw and Chadwick 1980, Hossner and Hons 1992). Stabilization of mine tailings is, therefore, essential, and revegetation is generally the most effective solution.

Revegetation of tailings commonly takes place under dryland conditions; however, use of a wetland cover provides an alternative to these traditional methods (Beckett et al. 1997, McCabe et al. in press). Under wetland conditions, tailings are less prone to wind erosion. Continuous water-logging leads to immobilization of metals due to precipitation as sulfides (Gambrell 1994), and tailings are less likely to produce acid mine drainage.

Plants used for revegetation of metal-contaminated mine tailings must be able to grow in elevated metal concentrations. It is also advantageous if plants used for this purpose have low nutrient requirements, as fertilizer amendments can increase the cost of revegetation.

Typha latifolia L. (cattail), *Phragmites australis* L. (common reed), and *Scirpus acutus* Muhl. (hardstem bulrush) are some of the species that have been used for revegetation of mine tailings under wetland conditions (Nawrot 1981, Nawrot and Yaich 1982, Beckett et al. 1997). Until now, the possibility of using *Glyceria fluitans* (L.) R. Br. (floating sweetgrass) for this purpose had not been considered. *Glyceria fluitans* is a wetland grass that grows rooted in the soil/sediment. It normally grows under submerged conditions, with the leaves floating on the water surface (hence the name floating sweetgrass); however, it can also grow as an emergent plant. In 1994, *G. fluitans* was found growing in the tailings pond of an abandoned lead/zinc mine at Glendalough, Co. Wicklow, Ireland (Beining and Otte 1996). Lead and zinc concentrations in the tailings pond were greatly elevated compared to background concentrations normally present in sediment (Beining and Otte 1996) and were similar to concentrations present in lead/zinc tailings from other mine sites (Smith and Bradshaw 1979). This indicated that *G. fluitans* could grow in tailings of elevated zinc and lead concentrations and might, therefore, be a suitable species for revegetation purposes.

Glyceria fluitans was also found growing in the nearby Lough Dan site (Beining and Otte 1996). While the Glendalough and Lough Dan sites are very similar in geology, appearance, and vegetation (Beining and Otte 1996), metal concentrations at Lough Dan (2.4 μmol g^{-1} Zn, 0.06 μmol g^{-1} Pb, 117 μmol g^{-1} Fe) are significantly lower than those at Glendalough (252 μmol g^{-1} Zn, 189 μmol g^{-1} Pb, 335 μmol g^{-1} Fe). *Glyceria fluitans* from Lough Dan therefore represented a population from a site without metal contamination.

The aim of this study was to establish the suitability of *G. fluitans* for revegetation of tailings under wetland conditions. A greenhouse experiment carried out earlier (McCabe and Otte 1997) indicated that *G. fluitans* from Glendalough and Lough Dan grew equally well on metal mine tailings, regardless of origin. In addition, a short-term greenhouse experiment indicated that growth of *G. fluitans* was similar over a range of different fertilizer treatments. These findings suggested that *G. fluitans* could grow in elevated metal concentrations and has a low fertilizer requirement (McCabe and Otte 1997).

In this paper, the results of subsequent outdoor experiments are presented. An outdoor microcosm experiment investigated (i) growth of *G. fluitans* of non-contaminated origin (Lough Dan site) on mine tailings from two other lead/zinc mines (Outkumpu-Zinc Tara Mines and Silvermines) and (ii) the effects of different fertilizer treatments on plant growth. In a field transplant experiment, growth of *G. fluitans* from Lough Dan on tailings from Glendalough was monitored.

MATERIALS AND METHODS

Outdoor Microcosm Experiment

Tailings for this experiment were obtained from Outokumpu Zinc—Tara Mines, Navan, Co. Meath (6°43′W, 53°42′N, grid reference O 848 710, elevation 50 m) and from Silvermines, Co. Tipperary (8°15′W, 52°48′N, grid reference R 171 181, elevation 149 m), both situated in Ireland (McCabe et al. in press). Tailings from these sites were similar in that they both originated from lead/zinc mines. However, due to their high limestone content, tailings from Tara mines are alkaline in nature, whereas tailings from Silvermines are acid-generating. This meant that growth of *G. fluitans* on different types of tailings could be investigated.

Tailings (approximately 100 kg) from both mine sites were collected in large plastic containers (50-L volume) referred to as 'tubs' from here on. Tailings were collected from the active tailings pond at Outkumpu Zinc—Tara Mines in July 1996. Tailings from Silvermines could not be collected until February 1997. Silvermines tailings had already been revegetated (McCabe et al. in press); therefore, they were taken from 1.5–2.0 m depth below the surface layer in order to obtain 'untreated' tailings for the experiment.

Tailings collected from both sites were transported to the Thornfield Horticultural Unit at University College Dublin. Due to logistical restrictions (volume and weight of material, space available, cost factor), there was a limit to the number of replications in this experiment, and only three replicates were used for each treatment. Tubs were placed outdoors, and the experiment was set up in a completely randomized design.

On 26 July 1996, stolons of *G. fluitans* were collected from Lough Dan, transported in plastic bags to the greenhouse, and washed thoroughly. Stolons of *G. fluitans* were transplanted into each of six tubs (three stolons per tub) containing tailings from Tara mines. *Bio Gromore* NPK fertilizer (7.0:3.0:5.8) had been mixed into tailings in three of these tubs at a rate of 13.7 g per tub (equivalent to 700 kg ha^{-1}). This rate of fertilizer application was similar to levels of fertilizer normally recommended for revegetation of mine tailings (Bradshaw and Chadwick 1980). Tailings in each of the remaining three tubs were not supplied with fertilizer. All tubs were flooded so that a water depth of approximately 15 cm covered tailings and plants grew submerged in this water. Water was added to tubs during drier periods (to the same depth) in order to ensure that tailings in all treatments remained under flooded conditions throughout the experiment. Water up to a depth of at least 10 cm covered the tailings at all times.

Tailings from Silvermines could not be obtained at the same time as those from Tara mines; hence, there were differences in the date of experimental set-up and length of growing season used for *G. fluitans* grown on tailings from each mine. Apart from this, the set-up was the same for both experiments. *Glyceria fluitans* stolons were transplanted into tubs containing tailings from Silvermines on 19 March 1997. NPK fertilizer was applied at the same rate as above. *G. fluitans* grown in these tailings died in all but one tub after approximately three to four months. Therefore, transplanting of *G. fluitans* onto these tailings was repeated on 24 July 1997.

In all treatments, the total length of all new and existing leaves and shoots was measured at the start of the experiment. Leaf length was measured from the initial point of growth of the leaf to the endpoint at the tip. These measurements were repeated at various stages during the experiment and at the time of harvesting to monitor plant growth. On 17 September

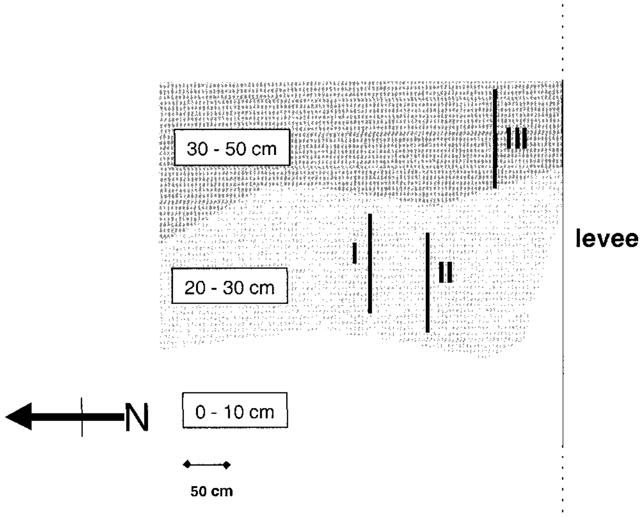

Figure 1. Approximate location of plants in the tailings pond at Glendalough for the field transplant experiment. The tailings pond (45 × 55 m) dates from around 1920 (P. Wynne, pers. comm.) and is surrounded by earth walls that lie approximately 1 m above the sediment surface. This diagram represents only part of the tailings pond. No *Glyceria fluitans* were transplanted at the water depth of 0–10 cm. *Glyceria fluitans* were transplanted in rows I and II at water depths of 20–30 cm, and in row III at a water depth of 30–50 cm (each row contained seven plants).

1997, *G. fluitans* plants that had grown on tailings from Tara mines were harvested. *Glyceria fluitans* grown on tailings from Silvermines were harvested on 24 September 1997.

Field Transplant Experiment

On 3 July 1996, plants of *G. fluitans* were collected from Lough Dan, Co. Wicklow (6°18′W, 53°05′N, grid reference O 142 043, elevation 200 m). These plants were kept moist and transported in plastic bags to the Glendalough Valley, Co. Wicklow (6°23′W, 53°00′N, grid reference T 095 962, elevation 140 m). All plants were washed thoroughly to remove any sediment that had adhered to the roots and were separated into individual stolons. Flowering heads were removed from all stolons to encourage new shoot formation. Each stolon consisted of two shoots measuring approximately 20–30 cm in length. The total fresh mass of each stolon ranged from 5.5 to 7.0 g. Plants were placed in rows to make it easier to recognize them during future visits. Rows were placed in an east-west direction to reduce shading effects of individual plants. Initially, *G. fluitans* stolons were transplanted into the tailings pond at Glendalough at locations referred to as rows 1 and 2 (see Figure 1). Each row consisted of seven stolons of *G. fluitans* planted at a distance of 30 cm apart. The water depth covering tailings at the time of transplanting was approximately 20–30 cm.

On 21 March 1997, an additional field transplant experiment was initiated to observe plant growth at a greater water depth than at rows 1 and 2. This time, plants were grown in row 3 in the tailings pond (see Figure 1) at a water depth of 30–50 cm. The length and fresh mass of these seven transplanted stolons of *G. fluitans* were similar to those of stolons that had been transplanted into the tailings pond earlier in July 1996.

On 26 September 1997, the numbers of live and dead shoots of transplanted stolons at each site were counted and recorded. These plants were harvested and transported back to the laboratory. The fresh and dry mass of live shoots, dead shoots, and roots of plants from each site were measured.

Analysis of Tailings, Sediment, and Porewater

Outdoor Microcosm Experiment. Five samples each of tailings from Tara mines and Silvermines were dried at 60 °C, finely ground, and stored for further analysis. Loss-on-ignition of all samples was determined after ashing a known weight (approximately 5.0 g) of dried tailings at 500 °C for six hours.

Nitrogen determinations of tailings from each site were carried out using a micro-Kjeldahl method (Hendershot 1985). Phosphorus was determined using the method of Murphy and Riley (1962). Blanks were included in every set of samples.

Tailings were also analyzed for metal concentrations. Approximately 200 mg of tailings were digested in Teflon bombs containing 2 ml of a strong acid mix HNO_3:HCl (4:1). Bombs were heated at 140 °C overnight until samples were completely digested (Otte et al. 1995). Once cooled, these were diluted to 10 ml with deionized water, left for one day, and then passed through 0.45 μm filters. Samples were analyzed for zinc, lead, iron, and magnesium using a flame atomic absorption spectrophotometer (FAAS, Solar Unicam 929). Analysis for potassium was carried out by flame emission spectroscopy using the same instrument. Teflon bombs, glassware, and all storage bottles used during metal analysis were soaked in 0.1 M HCl overnight and rinsed thoroughly in deionized water before use. Standards were made up in a 0.1 M HNO_3 solution. Inter-laboratory standard reference samples 'Soil Rendzina S-SP', supplied by Glen Spectra Reference Materials, England, were also analyzed for metal concentrations. Concentrations deviated, on average, by 10% (Zn), 11% (Pb), 13% (Fe), 12% (Mg), and 3% (K) from certified values.

During the experiment, the pH of tailings from both sites was measured on a monthly basis using a portable

Table 1. Mean ± standard deviation and significance (probability) of differences in pH, loss-on-ignition (LOI g 100 g^{-1}), and element concentrations (μmol g^{-1}) of tailings from Tara mines and Silvermines; (n=5); degrees of freedom = 1.

Variable	Tara Mines	Silvermines	F Value	P Value
pH	7.5 ±0.1	7.2 ± 0.1	27.38	0.002
LOI	0.8 ± 0.1	7.2 ± 0.9	149.25	0.000
Nitrogen	3.3 ± 4.7	5.7 ± 5.9	0.39	0.550
Phosphorus	1.5 ± 1.1	2.5 ± 0.6	2.22	0.175
Potassium	44 ± 7	77 ± 12	28.67	0.000
Zinc	227 ± 55	224 ± 27	0.00	0.972
Lead	11 ± 2	34 ± 2	427.67	0.000
Iron	413 ± 59	2584 ± 315	444.21	0.000
Magnesium	1863 ± 72	2104 ± 153	8.93	0.024

pH electrode (model WTW Wissenchaftlich Technische Werkstatten D 812 Weilham) and meter (WTW Typ E 50). Eh was also measured during the experiment with a portable redox meter and calomel reference electrode (incorporated with pH meter).

Two dialysis vials were placed into tailings in each tub at a depth of 20 cm to enable collection of porewater samples. These consisted of 25-ml polyethylene scintillation vials that contained deionized water and were covered with 20-μm-mesh Nytal P 20 nylon fabric. After a few weeks, water in these vials would have equilibrated with the surrounding water in the tailings so that the composition of water in the vials should be the same as that of tailings porewater (see also Beining and Otte 1996). On 10 September 1997, prior to harvesting of the plants, dialysis vials were collected, ensuring that they were kept airtight to prevent oxidation of ferrous iron from occurring. In the laboratory, porewater samples from one of the vials in each tub were filtered through a 0.45 μm filter (Gelman Sciences SuporR-450 Membrane Filter). These samples were acidified with a drop of concentrated HCl and stored at 4 °C for future analysis. Porewater samples were not digested prior to elemental analysis. The pH and electrical conductivity were measured for the non-acidified replicate porewater samples from each tub immediately.

Field Transplant Experiment. Three samples each of tailings material from transplant rows 1, 2, and 3 of the tailings pond at Glendalough and sediments from Lough Dan were collected from each row at the time of transplanting. These were analyzed for loss-on-ignition and elemental concentrations following the methods described above.

Analysis of Plant Material

Plants from both experiments were separated into individual plant parts (i.e., live shoots, dead shoots, and roots). All plant material was washed and then dried at 60 °C for two or three days, after which the dry mass of all plant parts was measured. Plant material was finely ground and stored for further analysis.

Metal concentrations of plant material (200 mg) were determined using the methods outlined earlier for tailings. Standard reference samples (CTA-OTL-1 supplied by Glen Spectra Reference Materials, England) were also analyzed and concentrations deviated on average by 3% (Zn), 4.5% (Pb), 8.5% (Fe), and 12% (Mg) from certified values.

Statistical Analyses

Statistical analyses were carried out following Sokal and Rohlf (1995). Analysis of variance (ANOVA) was carried out to test for significant differences using Minitab 8.1 for Macintosh. Data expressed in percentages (i.e., ratios) were arcsine-transformed, and all other data were $\log_{10}$-transformed to obtain homogeneity of variance. A one-way ANOVA followed by Tukey's comparison of means test was carried out to compare treatments. Differences were regarded significant if the probabilities were smaller than 0.05.

RESULTS

Outdoor Microcosm Experiment

Characteristics of Tailings. Eh values of tailings in which *G. fluitans* plants were grown ranged from −40 to −100 mV and did not differ significantly between tailings in this experiment (data not shown). The pH of tailings from Tara mines was significantly higher ($p < 0.01$) than that of tailings from Silvermines (Table 1). There was a significant difference in loss-on-ignition (LOI) of tailings between both sites (Table 1), indicating that tailings from Silvermines had a higher organic matter content than tailings from Tara mines.

Nitrogen and phosphorus concentrations of tailings from both sites were similar and did not differ significantly between sites (Table 1). However, potassium

Table 2. Mean ± standard deviation and significance of difference between pH, electrical conductivity (EC) ($\mu S\ cm^{-1}$), zinc, lead, iron, and magnesium concentrations ($mg\ L^{-1}$) of porewater from Tara mines and Silvermines tailings (n=18); degrees of freedom = 1.

Metal	Tara Mines	Silvermines	F Value	P Value
pH	7.2 ± 0.2	6.9 ± 0.1	28.34	0.000
EC	1300 ± 500	3100 ± 400	92.49	0.000
Zinc	1.39 ± 1.5	12.17 ± 3.64	89.75	0.000
Lead	0.03 ± 0.02	0.1 ± 0.06	20.71	0.000
Iron	0.09 ± 0.06	0.2 ± 0.2	8.91	0.006
Magnesium	41.5 ± 27.5	192.7 ± 10.0	29.54	0.000

concentrations were significantly higher in tailings from Silvermines than in tailings from Tara mines ($p < 0.001$).

Results for metal concentrations indicated that there was no significant difference in zinc concentrations between tailings from Tara mines and Silvermines. Iron, lead, and magnesium concentrations were significantly higher in tailings from Silvermines than in tailings from Tara mines (Table 1).

Zinc, lead, iron, and magnesium concentrations, pH, nor electrical conductivity of tailings porewater samples differed between fertilized and unfertilized treatments. Therefore, results from individual treatments are not shown, and Table 2 only indicates the pooled mean metal concentrations of all porewater samples. Zinc, lead, iron, and magnesium concentrations were significantly higher in porewater samples of tailings from Silvermines than tailings from Tara mines (Table 2). The pH of porewater samples collected from tailings from Tara mines was significantly higher than that of porewater of tailings from Silvermines (Table 2). The electrical conductivity of porewater samples of tailings from Tara mines was significantly lower than for samples from Silvermines tailings (Table 2).

Growth of Plants. *Glyceria fluitans* grown on tailings from Silvermines died after a period of only three to four months after initial transplantation (March 1997) and again after a repeat transplantation (July 1997). As a result, plants were grown on the two types of tailings for different periods of time, and a statistical comparison between the two treatments was not deemed appropriate. However, fertilized and unfertilized treatments in the same tailings could be compared.

Leaf growth of *G. fluitans* on fertilized tailings from Tara mines (Figure 2 (i)) was significantly greater than that of plants grown on unfertilized tailings ($p = 0.01$, $F = 20.83$, degrees of freedom = 1). Leaf growth of *G. fluitans* on tailings from Silvermines (Figure 2 (ii)) did not differ significantly between fertilizer treatments tailings ($p = 0.444$, $F = 0.72$, degrees of freedom = 1).

There was a significant difference in biomass of all plant parts between fertilizer treatments for *G. fluitans* grown on tailings from Tara mines (Figure 3 (i); Table 3). Live shoot, dead shoot, and root biomass were much greater on fertilized than unfertilized tailings ($p < 0.05$). Biomass of live shoots, dead shoots, or roots of *G. fluitans* grown on tailings from Silvermines (Figure 3 (ii); Table 3) did not differ between fertilizer treatments.

For *G. fluitans* grown on tailings from Tara mines, none of the following variables differed significantly between fertilizer treatments: concentrations of nitrogen, phosphorus, potassium (data not shown), zinc, lead, iron, and magnesium (Figure 4) in any of the plant parts. For Silvermines tailings, zinc concentrations of *G. fluitans,* in dead shoots only, varied significantly between fertilizer treatments (Table 4), with concentrations of zinc in dead shoots of fertilized

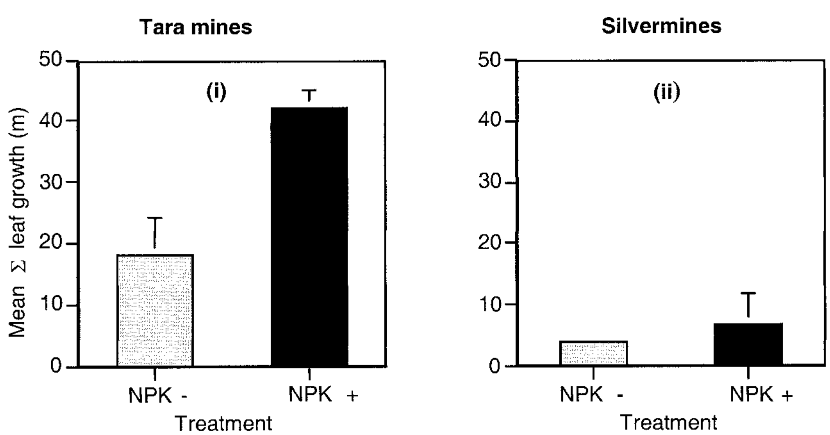

Figure 2. Mean sum (Σ) of leaf growth (m) of *Glyceria fluitans* grown in tailings from (i) Tara mines and (ii) Silvermines, without NPK fertilizer (NPK−) ■ and with (NPK+) NPK fertilizer ■; bars indicate standard deviations (n = 3).

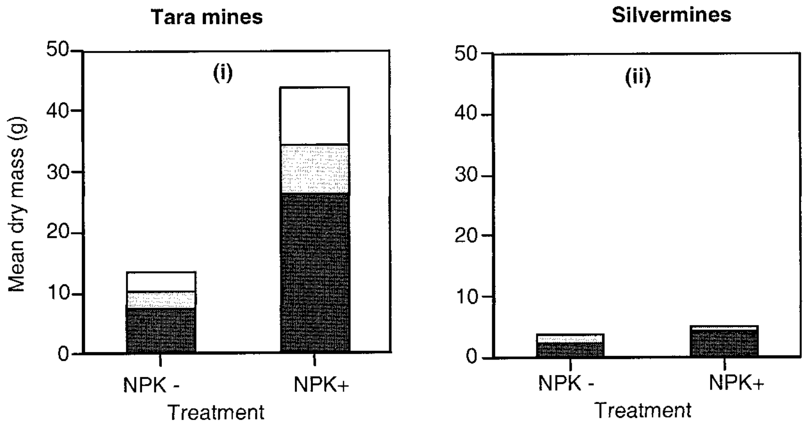

Figure 3. Mean dry mass (g) of live shoots □, dead shoots ▤, and roots ■, of *Glyceria fluitans* grown in tailings from (i) Tara mines and (ii) Silvermines, without (NPK−) and with (NPK+) NPK fertilizer, (n = 3). For significance of differences between treatments, see Table 3.

plants being lower than those of unfertilized plants. The other variables, concentrations of nitrogen, phosphorus, potassium (data not shown), lead, iron, or magnesium in any of the plant parts, again did not differ between treatments.

Field Transplant Experiment

Results for the analyses of the tailings material from each of the three transplant rows in the pond and from Lough Dan are shown in Tables 5 and 6. The tailings throughout the pond were similar for all variables investigated. For zinc only, small but significant differences between rows were observed (Table 5).

Plants of *G. fluitans* were transplanted in row 3 (March 1997) at a later date than in rows 1 or 2 (July 1996) in order to compare any effects of time of transplantation or water depth on plant growth. Despite having grown in the tailings for a much shorter period, the total number of live shoots produced by *G. fluitans* was greater in row 3 (17 shoots) than in row 1 (13 shoots) or row 2 (7 shoots). As plants grew in the tailings pond for different lengths of time (fourteen months at rows 1 and 2 and six months at row 3), growth was also compared on a per-month basis. The number of live shoots produced per month by *G. fluitans* (Figure 5) was significantly higher at row 3 than at rows 1 or 2 ($p = 0.000$, $F = 24.53$, degrees of freedom = 2).

Total live shoot biomass for *G. fluitans* was greater in row 3 (3.587 g) than in row 1 (3.384 g) or row 2 (1.345 g). Monthly live shoot biomass production (Figure 6) by *G. fluitans* was also significantly higher ($p = 0.000$, $F = 14.65$, degrees of freedom = 2) at transplantation row 3 (0.5 g per month) than at rows 1 (0.2 g per month) or 2 (0.1 g per month). Dead shoot ($p = 0.585$, $F = 0.55$, degrees of freedom = 2) or root ($p = 0.391$, $F = 0.97$, degrees of freedom = 2) biomass production per month by plants did not differ between rows. There was no significant difference in zinc, lead, or iron concentrations of live shoots, dead shoots or roots of *G. fluitans* (Figure 7) between transplantation rows within the pond (Table 7).

Table 3. Statistical analysis of differences in biomass due to fertilizer treatment (see Figure 3). A one-way analysis of variance on $\log_{10}$-transformed biomass data of live shoots, dead shoots, and roots of *Glyceria fluitans* grown on tailings from Tara mines and Silvermines. Values are significance (probabilities P) of differences due to fertilizer treatment (− NPK and + NPK); degrees of freedom = 1.

	Tara Mines		Silvermines	
Plant Part	F Value	P Value	F Value	P Value
Live shoots	13.63	0.021	0.13	0.740
Dead shoots	11.44	0.028	0.09	0.777
Roots	17.84	0.013	0.72	0.445

DISCUSSION

Outdoor Microcosm Experiment

Characteristics of Tailings Material. Under oxidized conditions, tailings from Silvermines have a high acid-generating potential. Due to the high limestone content of tailings from Tara mines, no net acid-generation takes place, and these tailings have an alkaline pH (McCabe et al. in press). Throughout this experiment, tailings from both sites were kept under permanently flooded conditions. Eh values ranging from −40 to −100 mV were measured, indicating that tailings were under reduced conditions during the experiment. Tailings had circumneutral pH values (Table 1), which is

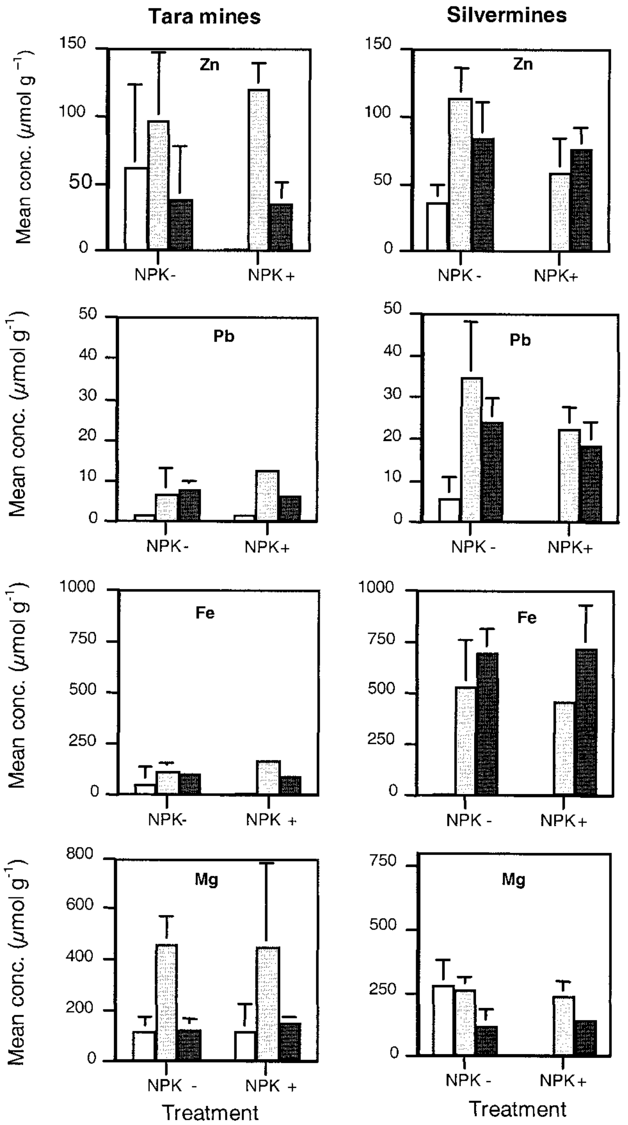

Figure 4. Mean zinc, lead, iron, and magnesium concentrations (μmol g^{-1}) of live shoots □, dead shoots ▤, and roots ■ of *Glyceria fluitans* grown in tailings from Tara mines and Silvermines, without (NPK−) and with (NPK+) NPK fertilizer; bars indicate standard deviations (n = 3). For significance of differences between treatments, see Table 4.

consistent with observations that, generally, the pH of soils and sediments under flooded, reduced conditions tends to be near neutral, regardless of soil acidity or alkalinity under non-flooded, oxidized conditions (Ponnamperuma 1972, Gambrell 1994).

The tailings from Silvermines had a higher organic matter content than those from Tara mines. This may be due to the fact that the tailings at Silvermines had already been revegetated for at least ten years (McCabe et al. in press). As tailings that originated from Tara mines were taken from an active tailings pond, there had never been any vegetative cover on these to act as a source of organic matter.

Nitrogen, phosphorus, and potassium concentrations in tailings from both sites were very low compared to concentrations normally present in sediments (Salomons and Förstner 1984). Lead, iron, and magnesium concentrations in tailings from Silvermines were much higher than in tailings from Tara mines. However, zinc concentrations did not differ significantly. Metal concentrations of tailings from both mines were generally much higher than levels normally present in sediments (Salomons and Förstner 1984). Elevated metal concentrations, low organic matter content, and low nutrient concentrations such as these are a common feature of metal mine tailings (Smith and Bradshaw 1979, Hossner and Hons 1992).

Salinity data for tailings are not shown here; however, the tailings from Silvermines are known to have a very high salt ($MgSO_4$) content (M. Johnson, pers. comm.; J. Good, pers. comm.).

Plant Growth on Tailings. Initially, growth of *G. fluitans* on both fertilized and unfertilized tailings from Tara mines was similar. However, after a period of three to four months, it became evident that the addition of NPK fertilizer to tailings significantly increased the rate of plant growth. This was reflected in a 40–50% plant coverage of unfertilized tailings compared to a 90–100% coverage of fertilized tailings after only six to eight months.

At the time of harvesting, a total of 270 plants per m^2 were growing on unfertilized tailings and 506 plants per m^2 on fertilized tailings from Tara mines. As a result, total fresh mass (per tub) produced by *G. fluitans* grown on unfertilized tailings (28.7 g/m^2/month) was significantly lower than that of *G. fluitans* grown on fertilized tailings (56.0 g/m^2/month) from Tara mines. This indicated that fertilizer treatment significantly improved biomass production. The nutrient content of sediment at Lough Dan, the site of origin of *G. fluitans,* was very low compared to concentrations normally present in sediments. It may be, therefore, that *G. fluitans* can grow in nutrient-poor conditions.

Growth and biomass production of plants on both fertilized and unfertilized tailings from Silvermines was very poor, and ultimately almost all *G. fluitans* that had been planted on these tailings died. As transplanting of *G. fluitans* onto these tailings took place at a different time of the year than onto tailings from Tara mines, it was possible that the differences in growth were due to seasonal effects. In order to investigate this, transplanting of *G. fluitans* onto tailings from Silvermines was repeated in July 1997, the same time of year that transplanting of *G. fluitans* onto tail-

Table 4. A one-way analysis of variance on $\log_{10}$-transformed zinc, lead, iron, and magnesium concentration data of live shoots, dead shoots, and roots of *Glyceria fluitans* grown on tailings from Tara mines and Silvermines (see Figure 4). Values are significance (probabilities P) of differences due to fertilizer treatment (− NPK and + NPK); degrees of freedom = 1. (NA = not available due to insufficient material for analysis).

		Live Shoots		Dead Shoots		Roots	
Metal	Source of Tailings	F Value	P Value	F Value	P Value	F Value	P Value
Zn	Tara mines	0.05	0.841	0.87	0.403	0.10	0.766
	Silvermines	NA	NA	8.24	0.045	0.07	0.803
Pb	Tara mines	0.02	0.890	1.31	0.316	2.09	0.222
	Silvermines	NA	NA	2.70	0.176	1.54	0.283
Fe	Tara mines	0.15	0.716	3.49	0.135	0.55	0.501
	Silvermines	NA	NA	0.02	0.897	0.00	0.992
Mg	Tara mines	0.07	0.799	0.23	0.654	0.89	0.399
	Silvermines	NA	NA	0.54	0.503	1.07	0.359

ings from Tara mines had taken place. However, once again, *G. fluitans* grew very little on tailings from Silvermines, and ultimately, almost all plants died. Therefore, the reason for poor growth of *G. fluitans* on tailings from Silvermines must have been due to some factor other than a seasonal effect at the time of transplanting.

Tailings from Silvermines had a higher organic matter content than those from Tara mines. This suggests that the nutrient status of tailings from Silvermines should have been more favorable for plant growth than that of tailings from Tara mines, and this then was not seen to explain the differences. The pH values of tailings from both sites were nearly neutral throughout the experiment. Differences in pH values between the tailings were small and therefore unlikely to explain the differences in growth of *G. fluitans* between treatments.

Electrical conductivity is broadly a measure of the total salt content (Kadlec and Knight 1996) and generally ranges from 10 to 300 μ mho cm^{-1} for inland surface waters. In this experiment, electrical conductivity of porewater samples taken from Tara mines tailings measured approximately 1000 μ mho cm^{-1} and those from Silvermines about 3000 μ mho cm^{-1}. Clearly, the electrical conductivity, and hence the salt content of porewater and tailings from Silvermines, was much greater than for porewater and tailings from Tara mines. Previous research indicated that one of the main reasons for poor growth of plants on tailings from Silvermines in initial revegetation trials was the high salt (magnesium sulfate) content and associated high electrical conductivity of these tailings (McCabe et al. in press). Magnesium concentrations were also greater in tailings and porewater from Silvermines than in those from Tara mines. It is possible, therefore, that the high salt ($MgSO_4$) concentrations in porewater of tailings from Silvermines adversely affected growth of *G. fluitans* by inducing salt toxicity.

Zinc concentrations of porewater from Silvermines tailings were much greater than in porewater of tailings from Tara mines (see Table 2). This suggests that *G. fluitans* grown on tailings from Silvermines were exposed to higher zinc concentrations than plants grown on tailings from Tara mines. Although statistical comparisons were not carried out due to differences in growth period, zinc concentrations in plants on Silvermines tailings were very similar to those on Tara mines tailings. Previous experiments (McCabe and Otte 1997) have indicated that *G. fluitans* can grow in elevated zinc concentrations. Therefore, poor growth

Table 5. Mean ± standard deviation and significance of differences between loss-on-ignition (LOI) (g $100g^{-1}$) and element concentrations (μmol g^{-1}) of tailings from rows 1, 2, and 3 of the tailings pond at Glendalough (n = 3; degrees of freedom = 2).

Parameter	Row 1	Row 2	Row 3	F Value	P Value
LOI	5.3 ± 0.1	5.4 ± 0.1	8.0 ± 1.6	4.45	0.065
Nitrogen	10.9 ± 3.4	9.6 ± 0.3	17.1 ± 2.6	4.92	0.066
Phosphorus	3.5 ± 1.2	3.1 ± 0.2	5.7 ± 0.9	4.80	0.069
Potassium	332 ± 28	308 ± 20	336 ± 101	0.16	0.852
Zinc	334 ± 10	292 ± 22	323 ± 17	6.10	0.025
Lead	121 ± 9	120 ± 10	137 ± 10	3.88	0.061
Iron	276 ± 18	299 ± 16	300 ± 123	0.11	0.894

Table 6. Mean ± standard deviation of pH, loss-on-ignition (LOI) (g 100g^{-1}) and element concentrations (μmol g^{-1}) of sediment from Lough Dan (n = 3).

Parameter	Value
pH	5.3 ± 0.6
LOI	4.8 ± 3.4
N	3.5 ± 2.7
P	0.9 ± 0.3
K	61 ± 12
Zn	2.4 ± 1.5
Pb	0.06 ± 0.06
Fe	117 ± 6

of *G. fluitans* on tailings from Silvermines is unlikely to have been due to the elevated zinc concentrations.

Lead and iron concentrations in tailings and porewater from Silvermines were much higher than the concentrations in tailings and porewater from Tara mines. Lead concentrations seemed to be much higher in *G. fluitans* grown on tailings from Silvermines compared to Tara mines. *Glyceria fluitans* grown on tailings from Silvermines had much higher iron concentrations than those normally present in plants, while those grown on tailings from Tara mines contained iron concentrations within the range characteristic of many plants (Allen et al. 1974). Many of the symptoms of lead and iron toxicity (Mehra and Farago 1994) observed for *G. fluitans* grown on tailings from Silvermines were not a feature of plants grown on tailings from Tara mines. It is likely, therefore, that the elevated lead and iron concentrations in tailings from Silvermines were toxic to *G. fluitans.*

Field Transplant Experiment

Characteristics of Tailings. The organic matter content and nutrient (N, P, and K) concentrations of tailings throughout the pond were similar and were lower than those normally present in wetland soils or sediments (Salomons and Förstner 1984, Faulkner and Richardson 1989).

Lead and iron concentrations were similar throughout the tailings pond. Zinc concentrations were, however, slightly lower at row 2 than at rows 1 or 3. This is probably due to the fact that the metal concentrations of tailings can often vary greatly, depending on the efficiency of recovery processes during metal ore smelting and extraction operations (Bradshaw and Chadwick 1980). The mine site at Glendalough is quite old (Beining and Otte 1996); therefore, it is likely that the methods of extraction used when this mine was in operation were not as efficient as those of the present day.

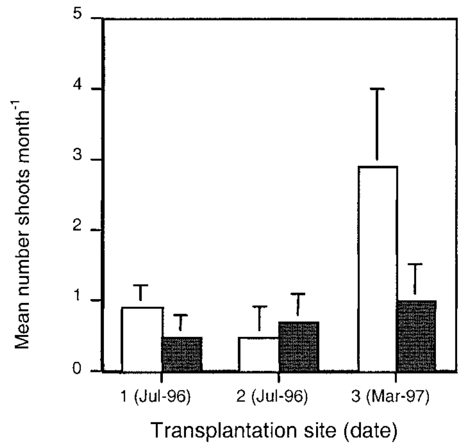

Figure 5. Mean number of live shoots □ ($p < 0.001$) and dead shoots ■ (differences not significant) produced per month by *Glyceria fluitans* from Lough Dan grown in the tailings pond at Glendalough at rows 1, 2 (July 1996), and 3 (March 1997). Bars indicate standard deviations (n = 7).

Plant Growth. *Glyceria fluitans* grew for a period of only six months in row 3, whereas plants in rows 1 and 2 had been growing in the tailings pond for a period of fourteen months. However, total live shoot production and percent cover of unvegetated tailings by *G. fluitans* were greater in row 3 than in rows 1 or 2. The number of live shoots produced per month by *G. fluitans* grown in transplantation row 3 (three shoots) was also greater than that of *G. fluitans* in row 1 (one shoot) or row 2 (one shoot). As a result, *G. fluitans* grown in row 3 produced significantly more biomass (0.9 g per month) than plants grown in rows 1 (0.5 g per month) or 2 (0.4 g per month). Similarly,

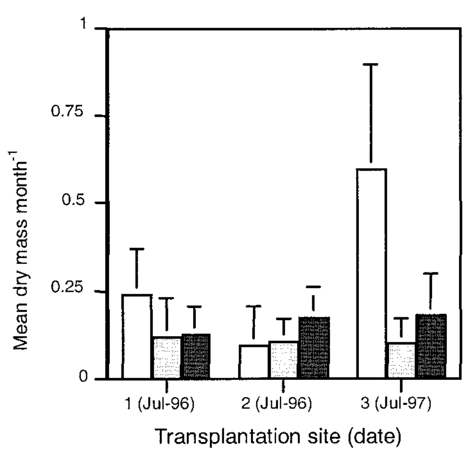

Figure 6. Mean dry mass (g) of live shoots □ ($p < 0.001$), dead shoots ▒ (differences not significant), and roots ■ (differences not significant) produced per month by *Glyceria fluitans* from Lough Dan grown in the tailings pond at Glendalough at rows 1, 2 (July 1996), and 3 (March 1997). Bars indicate standard deviations (n = 7).

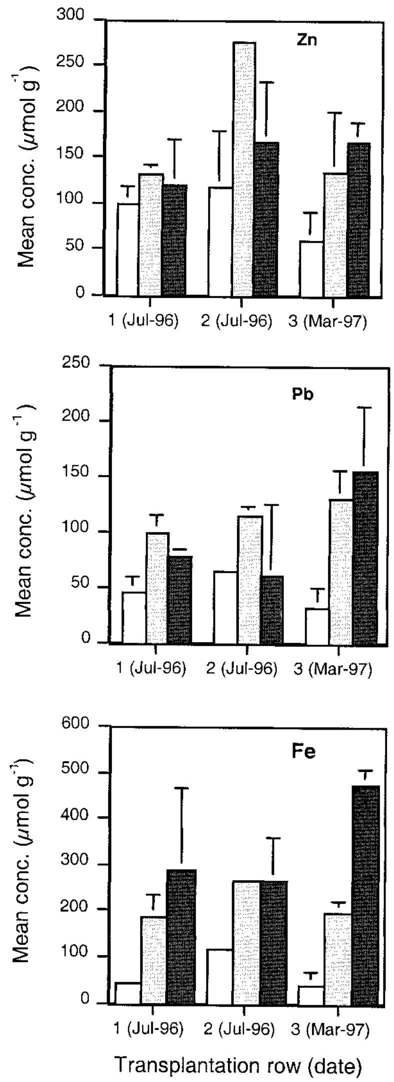

Figure 7. Mean zinc, lead, and iron concentrations (μmol g^{-1}) of live shoots □, dead shoots ▤, and roots ■ of *Glyceria fluitans* grown at rows 1, 2 (July 1996), and 3 (March 1997) of the tailings pond at Glendalough (bars indicate standard deviation (n = 3); there were no significant differences in metal concentrations of the various plant parts between rows).

total biomass production was greater in transplant row 3 than in rows 1 or 2. *Glyceria fluitans* in row 2 generally appeared to be in poor condition, and the proportion of biomass allocated to live shoots appeared to be lower than that allocated to dead shoots of plants in this row.

It is possible that differences in plant growth between seasons could explain greater growth and biomass production in row 3 (grown from March to September 1997) compared to rows 1 or 2 (grown from July 1996 to September 1997). However, if this was the case, it would be expected that absolute shoot and biomass production would be greater over the longer

Table 7. A one-way analysis of variance on $\log_{10}$-transformed zinc, lead, and iron concentration data of live shoots, dead shoots, and roots of *Glyceria fluitans* grown in the tailings pond at Glendalough (see Figure 7). Values are significance (probabilities P) of differences due to transplantation row (rows 1, 2, and 3); degrees of freedom = 2.

	Live Shoots		Dead Shoots		Roots	
Metal	F Value	P Value	F Value	P Value	F Value	P Value
Zinc	0.171	0.272	1.73	0.366	0.70	0.563
Lead	1.26	0.376	1.6	0.337	1.27	0.399
Iron	1.82	0.275	1.25	0.444	1.32	0.388

growth period of fourteen months (rows 1 and 2) compared to a period of only six months (row 3). Therefore, seasonal differences above cannot explain the differences in growth between transplant rows, and varying environmental conditions may have caused these differences.

During this experiment, the water depth in row 1, and to a greater extent in row 2, decreased considerably during the drier summer months. As a result, the water table was often well below the tailings surface in these areas, and plants grew in relatively dry conditions. However, throughout the experiment, *G. fluitans* in row 3 remained under waterlogged conditions. It may be that plant growth was reduced in transplantation rows 1 and 2 during the drier conditions. This would explain why the rate of shoot growth and biomass production of *G. fluitans* was much greater in row 3 than in rows 1 or 2. Changes in water depth in the tailings pond may also explain why *G. fluitans* grown in transplantation row 2 (the row that dried out most during the summer months) were in poor condition at the time of harvesting and produced considerably less live shoot biomass than plants in row 3.

These results are in agreement with the findings of a similar experiment carried out in the greenhouse (McCabe and Otte 1997) in which *G. fluitans* from Lough Dan and Glendalough grew taller and produced more biomass when grown under flooded compared to non-flooded conditions. Poor water retention or poor water infiltration are often characteristic features of mine tailings. Therefore, perhaps *G. fluitans* grown in row 2 and to a lesser extent in row 1 suffered from drought due to poor water availability to these plants. In addition, under non-flooded, oxidized conditions, changes can occur in soil pH, redox potential, metal mobility, and nutrient availability (Gambrell 1994), which can affect plant growth. As the tailings in row 3 remained under flooded conditions throughout the experiment, the chemical characteristics of tailings would not have altered, and growth of *G. fluitans* in these rows would not have been affected.

Zinc, lead, or iron concentrations of *G. fluitans* did not differ between transplantation rows. Therefore, the reason for better growth of plants in row 3 compared to rows 1 or 2 is unlikely to be due to any differences in the metal or nutrient composition of tailings. The fact that all metal concentrations were greatly elevated compared to levels normally present in other wetland plants (Kadlec and Knight 1996) indicates that *G. fluitans* can grow in tailings of elevated metal concentrations without obvious adverse effects on plant growth, even after a period of more than a year. This further indicates that *G. fluitans* is likely to be a suitable species for revegetation purposes.

Findings of this experiment have important implications for revegetation trials involving *G. fluitans.* A low water table could adversely affect growth of plants and ultimately the success of rehabilitation. It is essential, therefore, that care is taken in the design of the water supply for a wetland cover to ensure that the tailings remain flooded at all times. Therefore, precautions should be taken to ensure that, in the event of a prolonged period of drought, tailings will not dry out and become oxidized.

Nutrient concentrations of tailings at all three transplantation rows of the tailings pond were very low, and *G. fluitans* transplanted into the tailings pond were not supplied with any fertilizer. Nonetheless, plants grew well and spread out rapidly to cover previously unvegetated tailings, again indicating that *G. fluitans* has a low nutrient requirement. Therefore, if tailings are to be revegetated using *G. fluitans,* fertilizer costs can be kept to a minimum.

Our research indicates that *G. fluitans* can be easily established and grows well in metal mine tailings of the type produced by Outkumpu-Tara Mines Ltd. *Glyceria fluitans* seems to have a low nutrient requirement, which will reduce the cost of revegetation under wetland compared to dryland conditions. *Glyceria fluitans* does not appear to be a suitable species for revegetation of the tailings from Silvermines, which have much higher lead and iron concentrations and a very high salt content.

Using a wetland cover for revegetation of tailings means low operational and maintenance costs (Nawrot and Yaich 1982, Brix and Schierup 1989). The high rate of biomass production observed for *G. fluitans* (grown on tailings from Tara mines) means that it is a prolific organic matter producer. The formation of an organic matter layer over tailings has a three-fold advantage in that (i) it increases nutrient supply to plants, thus encouraging further plant growth and the invasion of additional species; (ii) it will perpetuate input of organic matter, which serves as a substrate for microbially mediated reduction reactions; and (iii) it will act as a barrier to maintain tailings under reduced conditions during periods of low water levels (Beckett et al. 1997). A wetland cover will improve the aesthetic quality of the area while also providing important wildlife habitats and recreational and educational facilities (Hammer and Bastian 1989). While previous studies (Johnson et al. 1978, Andrews et al. 1989) have indicated that there were no adverse effects of elevated plant metal concentrations on wildlife, it would be essential to monitor carefully all animals in such wetlands. It is our intention to confirm the findings of this study in a long-term and larger scale field trial in the future.

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