Initial Tree Establishment on Blocky Quarry Waste Ameliorated with Hydrogel or Slate Processing Fines

E. C. Rowe,* J. C. Williamson, D. L. Jones, P. Holliman, and J. R. Healey

ABSTRACT

Pocket planting reclamation techniques developed in the 1970s for revegetating blocky quarrying waste have met with very limited success, often because the low water-holding capacity of the waste and limited root development within a small volume of planting pocket material result in severe drought mortality. We tested pocket planting approaches for waste tip reclamation at Europe's largest slate quarry, and compared materials for enhancing the continuity of water- and nutrient-holding down into the interior of the waste tip. When small compost-filled pocket planting bags were placed above slate processing fines (SPF) or water absorbent cross-linked polyacrylamide gel ("hydrogel"), tree growth rates increased in comparison with pocket planting bags alone. The SPF significantly improved tree survival especially during severe drought, but survival was not enhanced by the use of hydrogel. The sorption characteristics of hydrogel indicated that its presence may help to reduce nutrient leaching, but that it may have a negative effect on nitrogen availability. A more likely explanation for the poor performance of pure hydrogel is that it did not maintain sufficient available water, because of discontinuities caused by shrinkage and movement of the hydrogel, and/or degradation of water-holding capacity with environmental exposure. However, the root growth observed in the hydrogel treatments suggests that this technique, if adapted to reduce the effects of hydrogel shrinkage by using finer-grade hydrogel, mixing it with other soil-forming material, and reducing its exposure to extremes of temperature or sunlight, might have the potential to improve the growth and survival of trees planted on sites where delivery of heavy materials such as SPF is impractical. Fine mineral processing waste is freely available at active quarries and should be seen as a key resource for reclamation schemes.

DEMANDS FOR MINERAL resources by society are continually growing, and have led to an increased incidence of severe land disturbance and consequently a search for ecologically responsible reclamation techniques (Winter-Sydnor and Redente, 2002). Tips of blocky hard rock waste (here defined as containing greater than 95% by weight of stones larger than 10 cm in diameter) are inhospitable to plant growth because of their poor water-holding capacity and limited capability to supply nutrients. Early suggested reclamation solutions for these wastes (e.g., planting into a pocket of peat-based compost; Sheldon, 1975) have proved unsustainable as they provide insufficient fine material to meet the water and/or nutrient demands of growing plants. Solutions implemented on some sites have included the regrading of waste spoil tips and the application of imported topsoil (Paschke et al., 2003). Many sites, however, contain large areas of blocky waste that are steeply sloping and difficult to access with large machinery. Engineering solutions may not be possible because of the costs of machine time, or because regrading would increase the area covered, increase the risk of pollution, or necessitate an expensive resurvey of tip stability. Engineering solutions may also be unacceptable on sites where they would be detrimental to conservation interests and aesthetics. Although spreading of imported topsoil over waste is a method frequently used in restoration, problems often occur with low or variable quality of the soil, and the introduction of weed seeds and contaminants (Land Use Consultants and Wardell-Armstrong, 1996). There is therefore a need to develop robust techniques for revegetating inaccessible slopes using materials that can be easily transported over difficult terrain.

Alternative reclamation techniques for less accessible sites include hydroseeding and the use of lightweight superabsorbent polymers for water storage (e.g., cross-linked polyacrylamide gel; Cano et al., 2002). Cross-linked polyacrylamide gel (hydrogel) can be obtained cheaply and has been used successfully to improve tree survival in arid environments and in horticulture (Callaghan et al., 1988; Woodhouse and Johnson, 1991; Bouranis, 1998; Wallace, 1998). Hydrogel may also reduce metal phytotoxicity by binding metals into nontoxic forms (Mitchell and Atkinson, 1992). When not cross-linked, polyacrylamide is water soluble, and is used as a flocculant, for example to reduce soil erosion. The cross-linked polyacrylamide used in this study, prepared from bis-acrylamide and acrylamide, is not water soluble but is capable of absorbing very large quantities of water to form a gel. Hydrogel is a cross-linked anionic copolymer, consisting of a saturated C backbone with amide and carboxylate side groups. When hydrated these side groups form both positive and negative charges, which have the potential to retain ionic nutrients and thus affect their availability to plants and their loss through leaching.

Safety concerns have been raised over the use of hydrogel in reclamation schemes because newly manufactured hydrogel contains monomeric acrylamide, a known neurotoxin and carcinogen (International Agency for Research on Cancer, 1994), and there may also be the potential for subsequent polymer degradation and release of the monomer. Previous studies have shown that levels of acrylamide in newly manufactured hydrogel are within the U.S. and European Union legal limits and that elevated acrylamide contents are only observed when the hydrogel is exposed to elevated temperature

E.C. Rowe and J.C. Williamson, Institute of Environmental Sciences, and D.L. Jones and J.R. Healey, School of Agricultural and Forest Sciences, University of Wales, Bangor, LL57 2UW, UK. E.C. Rowe, current address: Centre for Ecology and Hydrology, Orton Building, Deiniol Road, Bangor, Gwynedd, LL57 2UP, UK. Received 23 July 2004. Technical Reports. *Corresponding author (ecro@ceh.ac.uk).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: SPF, slate processing fines.

(35°C) over an extended period (Holliman et al., 2005). In addition, acrylamide is known to possess a short half-life in soil (Lande et al., 1979). On this basis, we expected the risk of ground water contamination by acrylamide to be small.

Processing of quarried rock often yields fine particulate material. While this waste is denser than hydrogel, it has the advantage of being available in large amounts at working quarries and is generally free from weed seeds, so fine processing waste could be used directly to increase the quantity of fine material at pocket planting sites.

The objective of this study was to evaluate the potential use of hydrogel and slate processing fines (SPF) to improve the survival rate and growth of trees planted into small bags of compost for the reclamation of blocky areas of a mineral extraction quarry, where previous restoration strategies have been unsuccessful. In particular, we aimed to test hypotheses that: (i) trees can be established on blocky quarry waste without mechanical alteration of the waste, (ii) hydrogel and SPF increase rates of tree establishment and growth, and (iii) hydrogel and SPF do not reduce the uptake of available nutrients by plants.

MATERIALS AND METHODS

Site Description

Penrhyn Quarry is the largest slate extraction facility in Europe and is located in Bethesda, North Wales, UK (53°11′15″ N, 4°4′45″ W). The entire quarry site covers an area of approximately 265 ha of which approximately half is covered by mineral extraction (slate) waste tips. The average elevation is 200 m above mean sea level, mean annual precipitation is 2260 mm, mean annual air temperature is 9.3°C (minimum of −6.0°C, maximum of 29.5°C), and mean annual ground temperature at a 10-cm depth is 9.9°C. The waste tips typically exceed 10 m in thickness and consist mainly of stones and blocks (maximum length = 10–1000 mm). There is little evidence of fine material on the surfaces of the tips and presumably most of this material has been lost from the surface due to water erosion. Waste tipping in the study area within the quarry was performed in the 1950s and the area was largely undisturbed for more than 40 yr before the study, but vegetation development through primary succession was very limited due to the poor water and nutrient holding capacities of the substrate. A point survey showed that only 1.3% of the site had plant cover, consisting mainly of mosses and small crassulacean acid metabolism (CAM) plants (*Sedum* spp.), the rest being bare rock with no trees. Areas within the quarry where similar waste was tipped in the late 19th century still have a very low density of established trees.

Design and Construction

Experimental reclamation test plots were established in March 2001 on an area of freely draining, blocky slate consisting of three small *penclips* (elongated mounds built up by forward tipping) and the gullies between them. The site was isolated using an electric fence to prevent grazing by sheep. The experiment was laid out in a randomized complete block design. The site was divided into nine blocks, three on each of three slope directions: approximately south-, west-, and east-facing. South-facing slopes consisted of the tops of the penclips, and thus were less steep and contained a greater proportion of fine material at the surface than the east- and west-facing slopes. A contrast was therefore planned between south-facing slopes and east- or west-facing slopes. Within each block, three plots of either 4 × 5 m or 7 × 3 m were marked out. The study consisted of three treatments that were assigned to each of the three plots at random. Two or three trees per species were planted in each plot. Three types of tree were used in the trial, namely willow cuttings and common alder and Italian alder seedlings. The trees were planted into 3 L of peat-free compost enclosed within hessian bags, a strategy that has proved successful on areas with finer substrate elsewhere in the quarry. Planting directly into the substrate would have resulted in near-certain death of the trees in the case of the control treatment, because of the large proportion of air-filled space in the substrate on the experimental site (Sheldon, 1975).

Treatment 1 (control) consisted of placing the compost-filled bags with trees directly into the blocky slate substrate. Osmocote (Scotts Co., Marysville, OH) controlled-release fertilizer (NPK 15:10:10 + 2 MgO + trace elements) was added to the compost at a rate of 2.8 g L^{-1}. This formulation is designed to release nutrients over a period of 20 to 22 mo at an average soil temperature of 16°C.

Treatment 2 (SPF) was similar to Treatment 1 except that the compost bags were placed on top of a large pocket (50 L) of slate processing fines into which the same controlled-release fertilizer had been previously mixed at a rate of 13.1 g per tree, in addition to the 2.8 g L^{-1} in the compost bag. The SPF is a by-product of slate processing and had a particle-size distribution of 70% sand, 11% silt, and 19% clay, equivalent to a sandy loam texture, and an organic C content of 0.2%, total N content of <0.01%, bulk density of 1.41 g cm^{-3}, pH of 8.1, and Olsen P of 2 mg kg^{-1}.

Treatment 3 (hydrogel) was identical to Treatment 1 except that 150 g of dry hydrogel (Aquastore; Vitagrow Ltd., Lancashire, UK), and no SPF, was added to the bottom of a preexisting or prepared hollow in the surface of the slate waste tip above which the compost-filled bags were placed. Coarse-grade anionic polyacrylamide gel was used (4% > 4 mm and 10% < 1 mm, anhydrous) with sodium as the associated cation. The amount of added hydrogel was calculated to be sufficient to supply the water requirements of a tree with a 1-m^2 canopy, transpiring at 2 mm d^{-1}, for 4 wk without rain. The same controlled-release fertilizer was similarly mixed with the hydrogel before placement at a rate of 13.1 g per tree, in addition to the 2.8 g L^{-1} in the compost bag.

The tree species used were selected for their ability to colonize slate waste tips. The willow, *Salix caprea* × *S. cinerea* = *S.* × *reichardtii* A. Kerner, is a natural hybrid that was observed to be a common early colonizer of finer areas of slate waste on the study site. It has a broad distribution on disturbed habitats in Britain and is an effective colonizer of bare ground, due in part to the rapid growth of its saplings relative to those of other woody species (Grime et al., 1988). Common alder [*Alnus glutinosa* (L.) Gaertner] has also performed well in slate waste revegetation projects (Sheldon, 1975). Its natural populations are most common on moist soils, and it is confined to streamsides in drier climates (Claessens, 2003). However, Claessens (2003) also observes that the capacity of common alder to produce a large and deeply penetrating root system enables it to exploit a large volume of soil allowing successful growth on relatively dry sites, and this species has been used successfully on reclamation sites that are quite dry; it is relatively drought tolerant after the seedling stage (Grime et al., 1988). Italian alder [*Alnus cordata* (Lois.) Duby] is very drought-resistant and tolerant of infertile soils (Curto, 1976), as demonstrated by nursery drought experiments by Borghetti et al.

(1989), and has an extensive root system (Claessens, 2003). Italian alder was introduced to Britain in 1820 and has long been used in France for forest restoration, where it has been found to tolerate comparatively dry and infertile soils (Matthews, 1987). It also has the advantage of being unpalatable to sheep (Bending et al., 1999). Alder species show rapid early rates of growth, and their capacity to act as soil improvers (through improved nitrogen and soil organic matter content and physical structure) has been long recognized (e.g., Matthews, 1987; Moffat and Roberts, 1989). Common alder, gray willow (*Salix cinerea* L.), and goat willow (*S. caprea* L.) all have widespread distributions across Europe (including UK); however, the native range of Italian alder is confined to southern Italy and Corsica (Gamisans, 1983).

Willows were planted as fresh hardwood cuttings (approximately 12 cm long × 3 cm in diameter), obtained from a single tree that had colonized nearby slate waste. Alders were planted as nursery-raised 1-yr-old seedlings, 20 to 30 cm in height. Common alder trees were of local provenance. Where possible, bags were placed into crevices in the waste to reduce wind exposure, but rearrangement of stones was avoided. The most favorable planting positions within each plot were chosen subjectively for all treatments.

Mortality and growth of trees were assessed on 17 Oct. 2001, 21 Aug. 2002, and 29 Oct. 2003. Trees that had no living leaves or green buds were considered to have died. Stem height was measured as the vertical distance from the stem base to the highest living point. Stem basal diameter was measured above the zone of basal thickening and converted to basal area assuming circular stems; for multiple-stemmed trees, stem basal areas were summed. Total basal area is a reliable indicator of tree shoot biomass (Rowe and Cadisch, 2002). For willow cuttings, the diameters of regrowing shoots were measured, rather than the diameter of the cutting.

Mortality and growth were analyzed separately for each year. Mortality (numbers of dead or missing trees as a proportion of the number planted) was analyzed with the IRREML procedure (Engel, 1997) using Genstat (Payne et al., 1987). The significance of differences was tested using the Wald statistic and pairwise comparisons were made using the RPAIR procedure (Thissen and Goedhart, 2002). Tree mortality caused the design to become unbalanced and so growth data for the first two years were analyzed using the AUNBALANCED procedure, using a randomized complete block design. After three years, too few trees remained alive for growth data analysis.

Characterization of Hydrogel, Slate Processing Fines, and Compost

Using hydrogel to fill large pores within an effectively inert substrate represents a novel and extreme use of the hydrogel, in which its properties are not buffered by contact with soil. Therefore, it is important to understand the mechanisms by which pure hydrogel affects plant water and nutrient supply.

To determine the water release characteristics of hydrogel, distilled water was added to the dry polymer in ratios of 2, 3, 5, 10, 20, 30, 50, 100, 200, and 400:1 (w/w), and left for 48 h to equilibrate. Excess water was removed, and the water potential measured using a WP4 Dewpoint Potentiometer (Decagon Devices, Pullman, WA). This measures the water potential of a sample by determining the relative humidity of the air above the sample in a closed chamber at temperature equilibrium. The sample was then weighed, and water content was determined after drying at 105°C for 24 h. For SPF, distilled water was added to successive 5-g samples in different ratios by weight, until saturation was reached. Saturated samples were drained on filter paper, and water potential was measured after equilibrating for 48 h.

Ammonium, nitrate, phosphate, and potassium sorption isotherms were determined by equilibrating hydrogel or SPF in solutions of NH_4Cl, KNO_3, KH_2PO_4, and KCl, respectively. Hydrogel was added at a rate of 1 g hydrogel L^{-1} to solutions containing 0, 0.2, 0.4, 0.6, 0.8, or 1.0 mmol L^{-1} N, P, or K at pH 7.0, shaken for 2 h, and left to equilibrate for 48 h after which the supernatant was recovered for analysis. Concentrations of NH_4^+ and NO_3^-, PO_4^{3-}, and K^+ were determined with a San^{2+} segmented flow autoanalyzer (Skalar, Norcross, GA), colorimetrically according to Murphy and Riley (1962), and using a PFP7 flame photometer (Techne, Burlington, NJ), respectively. Amounts in the sorbed phase were calculated as the difference between the amount initially supplied and the amount remaining in the supernatant after equilibration. Sorption isotherms for SPF were obtained using the same procedure, except that the SPF-to-solution ratio was 1 g to 5 mL of solution.

Analyses of total carbon and nitrogen, plant-available nutrients, pH, and electrical conductivity were performed on the compost used in planting bags, before addition of controlled-release fertilizer. These analyses were also performed on old compost, SPF, and hydrogel recovered 42 mo after tree planting. Carbon and nitrogen contents were measured using a CHN2000 analyzer (LECO, St Joseph, MI). Plant-available phosphate and cations were measured using the Mehlich 3 extraction procedure (Mehlich, 1984). Electrical conductivity and pH were measured in a 1:1 (v/v) soil to water suspension after shaking for 30 min (Rhoades, 1996). Hydrogel and SPF samples were also recovered 42 mo after tree planting and the same chemical analyses were performed. The water content of old hydrogel at saturation was determined by equilibration with excess distilled water, weighing, and then ashing the sample for 3 d at 500°C to determine the hydrogel content.

The phosphorus content of Italian alder leaves from the experiment after 42 mo was determined by the ignition method (Kuo, 1996). Leaves from Italian alders established on a deep soil site were also analyzed for comparison.

RESULTS

Tree Survival

During the first year, tree species effects were dominant (Table 1). A higher proportion of trees were established from planted common alder seedlings than from willow cuttings and from planted Italian alder seedlings ($P < 0.001$). Planting of trees into SPF significantly increased their survival during the first year ($P < 0.05$); in contrast, the planting of trees together with hydrogel had no significant effect on the rate of mortality ($P > 0.05$). The effect of slope aspect had no significant impact on tree survival in this or subsequent years ($P > 0.05$). Species and substrate treatment effects were clearer by the second-year (2002) measurement, by which time approximately twice as many trees had survived when planted into SPF in comparison with trees planted without it or with hydrogel ($P < 0.05$). Significantly more common alders than willows persisted until this time, with an intermediate number of Italian alders continuing to survive ($P < 0.001$). Between the 2002 and 2003 measurements there were two periods when there was no significant rainfall (<0.5 mm) for more than 2 wk (Fig. 1). Tree mortality between these sampling dates was severe; all of the trees planted without SPF or hydrogel died, and the number of survivors on the hydrogel treatment was not significantly different from zero ($P > 0.05$). Even on the most successful treatment, SPF, only 25% of the trees that were alive in 2002 survived until 2003, and only 10% of the trees planted with hydrogel survived. Tree species differences disappeared in the last season of measurement, because a higher proportion of the previously more successful common alder died than of the other species.

Tree Growth

Mean stem basal area of surviving trees increased more consistently over time than did stem height, which was prone to variability because of dieback and resprouting of some trees (Fig. 2). After the first year's growth, the basal stem area of common alder was greater than that of the other two species ($P < 0.05$); however, the difference in basal area between the Italian alder seedlings and willow cuttings was not significant. After the second year, the only significant difference in basal stem area between species was that common alders were larger than willow ($P < 0.05$). Willows sprouted long, slender shoots during the first year, taller than the other species, but by the second year crown height was similar for all three species ($P > 0.05$). Substrate amendment treatments did not significantly affect crown height in the first year ($P > 0.05$), but basal area was increased by the addition of both hydrogel and SPF fillers in the first and second years ($P < 0.01$), and by the second year trees planted without hydrogel or SPF were also shorter ($P < 0.01$). Interactions between tree species and substrate amendment treatments were not significant, and there was little variation in growth between blocks of different aspect.

Table 1. Percentage survival of trees of three species planted into compost-filled bags placed into the surface of blocky slate quarry waste either without filler material (control), or with slate processing fines (SPF) or cross-linked polyacrylamide gel (Hydrogel) beneath, during the first three years after planting.

	Common alder	Italian alder	Willow†	Mean
	% survival‡			
	2001			
Control	74	48	37	53a§
SPF	100	67	56	74b
Hydrogel	63	44	41	49a
Mean	79a	53b	44b	
	2002			
Control	44	37	11	31a
SPF	94	61	44	67b
Hydrogel	56	37	22	38a
Mean	65a	45b	26c	
	2003			
Control	0	0	0	0a
SPF	11	33	6	17b
Hydrogel	0	4	7	4a
Mean	4a	12a	4a	

† Willows were planted as cuttings, whereas alders were planted as saplings.
‡ Survival is expressed as a percentage of the number of trees planted in spring 2001.
§ Letters indicate significant differences ($\alpha = 0.05$) for the main effects.

Hydrogel and Slate Processing Fines Water-Holding

The great majority of the water held by the hydrogel was retained at potentials between field capacity (−0.05 MPa) and wilting point (−1.5 MPa), and so was available to plants. At equilibrium, new hydrogel retained 367 g water g^{-1} dry hydrogel, while at the wilting point the hydrogel retained only around 4 g water g^{-1} (Fig. 3). This is consistent with the hydrogel product specification that around 95% of the water held in the hydrogel is plant-available. The field capacity of SPF was similar to that of a coarse-textured soil at 0.30 g water g^{-1}, but

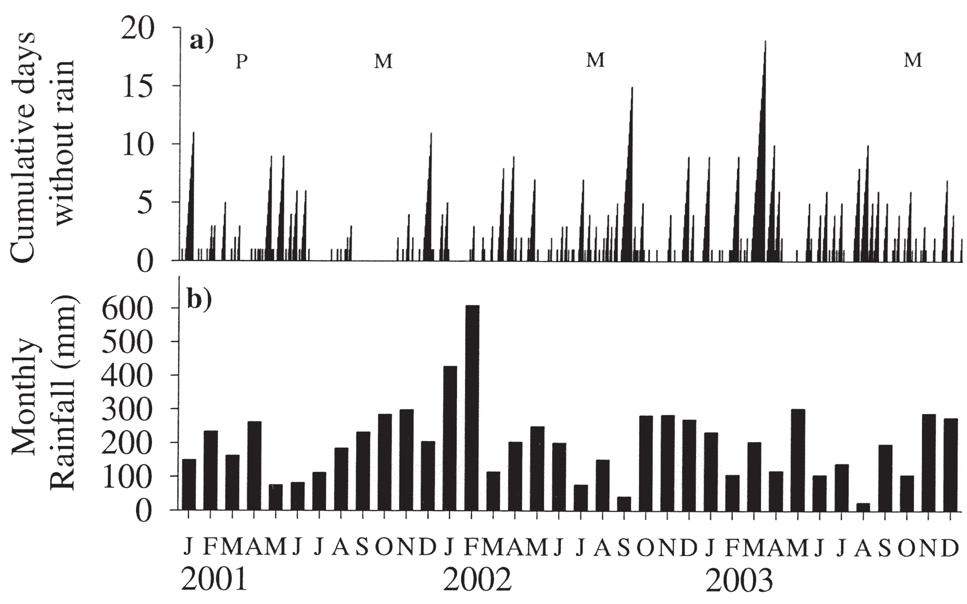

Fig. 1. Rainfall close to the study site: (a) cumulative days with less than 0.5 mm rain during the study period and (b) monthly rainfall. The term P indicates time of planting the experiment, while M indicates times of tree measurement.

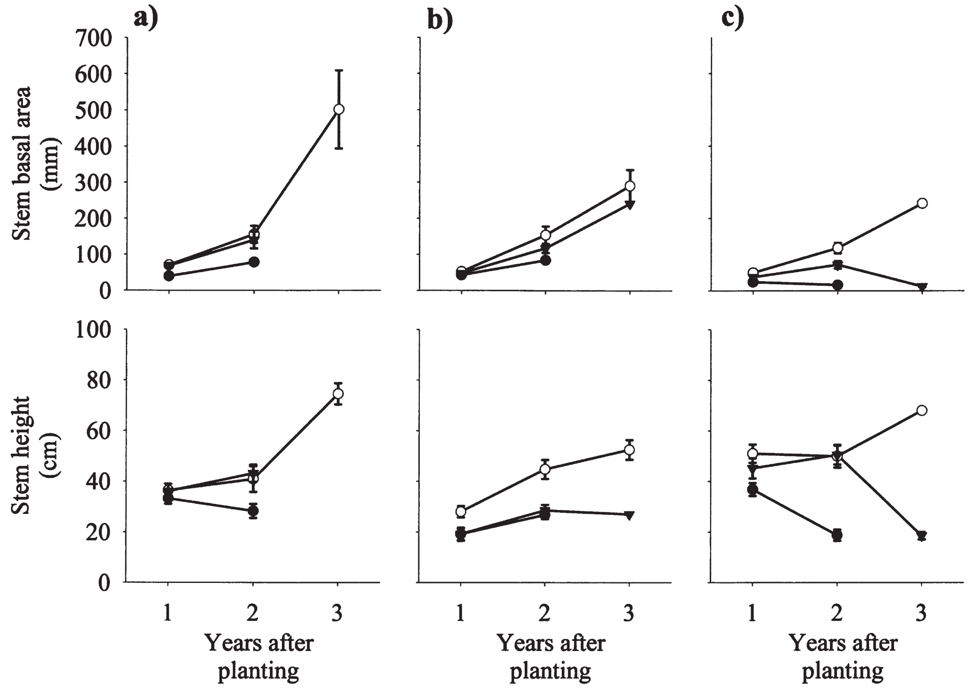

Fig. 2. Growth (stem basal area and height at one, two, and three years after planting) of three tree species planted into blocky slate waste in 3-L compost bags, without amendment, or with slate processing fines or hydrogel placed beneath for (a) common alder, (b) Italian alder, or (c) willow. Values represent means ± SEM.

water content at wilting point (0.01 g g^{-1}) was lower than expected. This implies that SPF contains fewer very small pores than a soil with similar particle-size distribution, so a smaller proportion of the water it contains is at a potential at which it is unavailable to plants.

After 42 mo in the field, the saturated water holding capacity of the hydrogel had reduced to 56 g water g^{-1} dry hydrogel. Organic matter additions did not cause the initial carbon content of the SPF (0.20%) to increase significantly (Table 2), and are therefore unlikely to have increased water-holding capacity. The SPF had apparently undergone some compaction, with measured bulk density of 1.65 g cm^{-3}, but this was very variable and so not significantly different from the starting bulk density (1.41 g cm^{-3}).

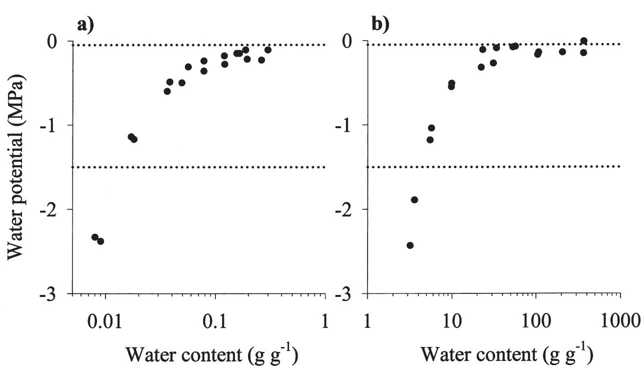

Fig. 3. Water release characteristics of (a) slate processing fines and (b) hydrogel. Note the difference in scale. Dotted lines represent the approximate upper (−0.05 MPa) and lower (−1.5 MPa) limits of plant-available water.

Hydrogel, Slate Processing Fines, and Compost Nutrient Contents

The compost used in planting bags was not rich in nitrogen, phosphorus, or potassium (Table 2), illustrating the importance of the additions of controlled-release fertilizer. After 42 mo in the field, the compost was further depleted in the main plant nutrient elements. However, the concentration of phosphorus in leaves of Italian alder at this time (mean for surviving trees on SPF and hydrogel treatments) was 1.23 mg g^{-1}, not different (*t* test; $P > 0.05$) to that in trees on deep soil (1.17 mg g^{-1}). Slate processing fines maintained a good supply of base cations, particularly calcium, and a correspondingly high pH. Cation concentrations in recovered hydrogel also remained high on a dry weight basis, particularly sodium, which was the main cation in the hydrogel when supplied.

Hydrogel and Slate Processing Fines Nutrient Retention Characteristics

In both hydrogel and SPF the maximum sorption per unit dry mass, as derived from fitted Langmuir curves,

Table 2. Selected properties of compost used in tree planting bags before planting (before addition of controlled-release fertilizer) and 42 mo after planting, and of cross-linked polyacrylamide gel (hydrogel) and slate processing fines (SPF) 42 mo after planting.

	Before planting	After 42 mo		
Property	Compost	Compost	SPF	Hydrogel
Total C, %	26.8 (4.2)†	12.8 (1.2)	0.23 (0.08)	19.1 (0.7)
Total N, %	0.50 (0.08)	0.46 (0.06)	<0.05	3.42 (0.12)
pH	5.13 (0.04)	5.42 (0.21)	7.96 (0.19)	5.88 (0.25)
Electric conductivity, μS cm^{-1}	31.33 (1.45)	21.60 (1.89)	55.60 (1.94)	74.60 (16.15)
Exchangeable Ca, mmol kg^{-1}	21.89 (0.89)	30.00 (5.47)	98.27 (0.49)	54.68 (8.43)
Exchangeable K, mmol kg^{-1}	7.58 (0.09)	4.19 (0.34)	2.23 (0.05)	13.62 (1.42)
Exchangeable Na, mmol kg^{-1}	5.22 (0.13)	4.40 (0.44)	4.26 (0.10)	72.72 (11.97)
Exchangeable P, mmol kg^{-1}	0.20 (0.01)	0.23 (0.05)	0.004 (0.001)	0.25 (0.08)

† Standard errors of the means are shown in parentheses.

was greater for cations than for anions (Fig. 4). This is consistent with the expected prevalence of surface negative charges on the SPF. The hydrogel used in the study contained amide and carboxylate side groups. At pH 7, the carboxylic acid groups would be expected to be deprotonated to produce R-CO_2^- (the external pH being above the pK_a of the carboxylic acid), and the nitrogen of the amide groups protonated to produce R-C(O)NH_3^+ (the external pH being below the pK_a of the amide). Thus both anions and cations can be sorbed by the hydrogel, but there is a preference for the latter. In comparison with the SPF data where saturation of the surface available sorption sites is clear, the relatively constant slopes of the Langmuir curves for both anionic and cationic nutrients in the hydrogel show that its exchange sites are not approaching saturation over the measured range of solution concentrations. This is further evidenced by the maximum sorption, which was very much greater (at least 400 times) by hydrogel than by SPF. This relates to the macro and molecular structure of the hydrogel, which holds a large volume of water within a relatively sparse polymer network giving this material a huge internal surface area, with a large number of exchange sites on the charged side groups. If sorption is expressed per unit volume of matric solution, ionic affinities are more comparable (Table 3), but remain high for NO_3^- and NH_4^+ in hydrogel. Thus while hydrogel is likely to be an excellent buffer for PO_4^{3-} and K^+, moderating their release and slowing leaching while maintaining adequate solution concentrations, it may interfere with the availability of nitrogen for plant uptake.

DISCUSSION

Survival rates of trees during the first two years were reasonably high (more than 50% of those planted as seedlings survived), considering the almost complete lack of intrinsic water-holding material visible at the surface of the waste tip before the treatments were applied (e.g., fine particles or organic matter). However, there were no long periods (>12 d) without rain during these years. In the third year, mortality was much greater, probably due to the combination of episodic drought and increasing water demand from the trees as they grew larger. Mortality in all three seasons was significantly reduced when SPF was added between the compost bags into which the trees were planted and the underlying blocky slate substrate, despite the fact that SPF had significantly increased their growth (doubling the growth in stem basal area of the surviving trees compared with untreated trees by the end of the second year). Excavation of two expired trees from each treatment revealed that roots did not extend beyond the planting material, whether this was a single bag or a bag plus additional amendment. The larger volume of material in the SPF treatment lead to larger rooting extents than in the other two treatments. The extra volume provided by hydrated hydrogel was small, although grains of more desiccated hydrogel were present within a greater volume of the tip. Together with the death (rather than stunting) of the trees, this suggests that the poor success rate was due to exhaustion of water-holding capacity.

The expected positive effect of hydrogel on tree survival, observed in other reclamation trials (Hüttermann et al., 1999; Chen et al., 2004), was not seen here. However, hydrogel did increase the growth rate of the surviving trees. Hüttermann et al. (1999) also reported an increase in growth of up to threefold in Aleppo pine (*Pinus halepensis* Mill.) seedlings in hydrogel-amended sandy soil, compared with unamended soil. Whitbread-Abrutat (1997) found, in contrast, that hydrogel failed to enhance tree growth in the reclamation of metalliferous mine wastes, but in that trial its failure to exclude toxic metals was the cause rather than its inability to supply water. Even if the proportion (4%) of trees treated with hydrogel surviving after 3 yr in this study is typical, this may still represent an important improvement over the 0% survival of untreated trees. The use of hydrogel for similar extreme applications may therefore still be worth developing, particularly in view of its enhancement of tree growth, relatively low cost (approximately US\$6 kg^{-1} or US\$1 tree^{-1}), lightweight and portable nature, and potential to improve performance through mixing with other soil-forming materials.

At least some of the increase in tree growth caused by inserting SPF or hydrogel below their planting bags was presumably due to the Osmocote fertilizer added to these materials. Because of the low inherent fertility of the blocky slate waste, tree growth is greatly improved by addition of nutrients as well as water-holding materials (Sheldon, 1975). Tree roots were commonly observed growing through both the SPF and hydrogel (Fig. 5), allowing access to the extra reserves of nutrients mixed with them. This demonstrated that the treatments tested did not fail because the hessian bags created a discontinuity acting as a barrier to root growth into adjacent

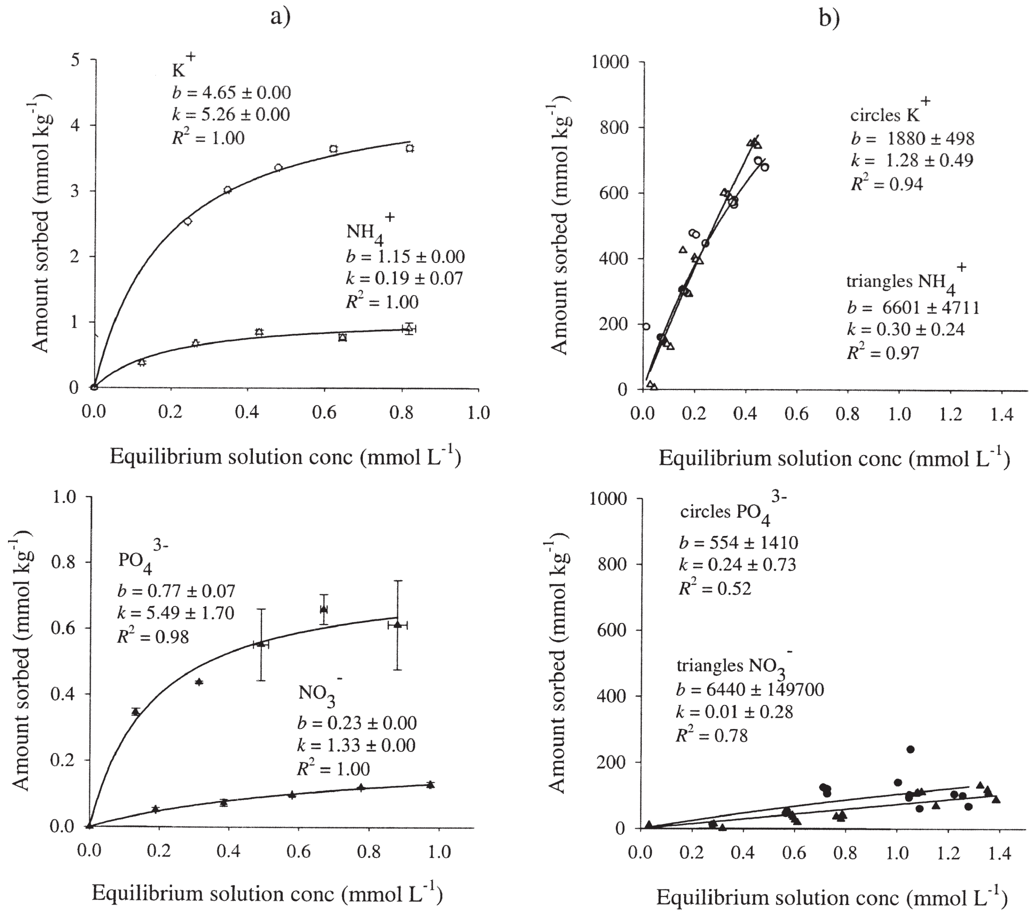

Fig. 4. Sorption characteristics for ammonium, potassium, phosphate, and nitrate ions in (a) slate processing fines and (b) hydrogel. Values from fitted Langmuir curves for maximum sorption (*b*) and the partition coefficient (*k*) are shown, ±SEM.

media. In fact, any hessian in contact with rock or other material decayed within a few weeks under the conditions on the site, allowing direct contact between the compost and media. Indeed, Hüttermann et al. (1999) reported that hydrogel increased the incidence of adventitious, more highly branching roots compared with the root system of Aleppo pine seedlings grown in control soil. The fact that roots were observed to grow freely both within the mass of hydrogel and within individual hydrogel grains demonstrates that sufficient oxygen was able to diffuse through the hydrogel, perhaps a consequence of the large grains of this hydrogel and the very coarse and open soil matrix.

The primary function of the SPF and hydrogel was to retain water between field capacity and wilting point

Table 3. Maximum sorption of plant nutrient ions by slate processing fines (SPF) and cross-linked polyacrylamide gel (hydrogel), expressed per liter of matric solution at a water potential of −0.1 MPa.

	Sorption	
Nutrient ion	**SPF**	**Hydrogel**
	mmol L^{-1} matric solution	
K^+	16.8	12.8
NH_4^+	4.2	45.0
PO_4^{3-}	2.8	3.8
NO_3^-	0.8	43.9

and supply water to tree roots. The mortality data show that in the field the SPF was more successful in doing this than the hydrogel. In the laboratory, by comparison, new hydrogel was able to take up significantly more water than SPF. The discrepancy may be due to inefficient use under field conditions by trees of water held within the hydrogel, because of discontinuities caused by swelling, shrinking, and slipping down into voids within the tip. Slow water diffusion into the interior of the large hydrogel grains may have limited the proportion of the rainfall that was taken up. However, when exposed to saturation by water, its uptake by the hydrogel was rapid (from anhydrous to full capacity in under 30 min), so it seems unlikely that water uptake was limited by the diffusion rate. The limited lifetime of hydrogel under field conditions is another factor. While hydrogel can remain in soil for at least five years, Holliman et al. (2005) found that swelling capacity decreased sharply within the first 18 mo to only 14% of its original capacity, and saturated water holding capacity after 42 mo measured in the current study had also reduced by around 85%. If hydrogel loses its ability to take up water, it will also not retain nutrients in plant-available form. By comparison, water and nutrient retention of SPF are expected to remain constant, because this material is relatively inert.

The moderate to high sorption constants for the major

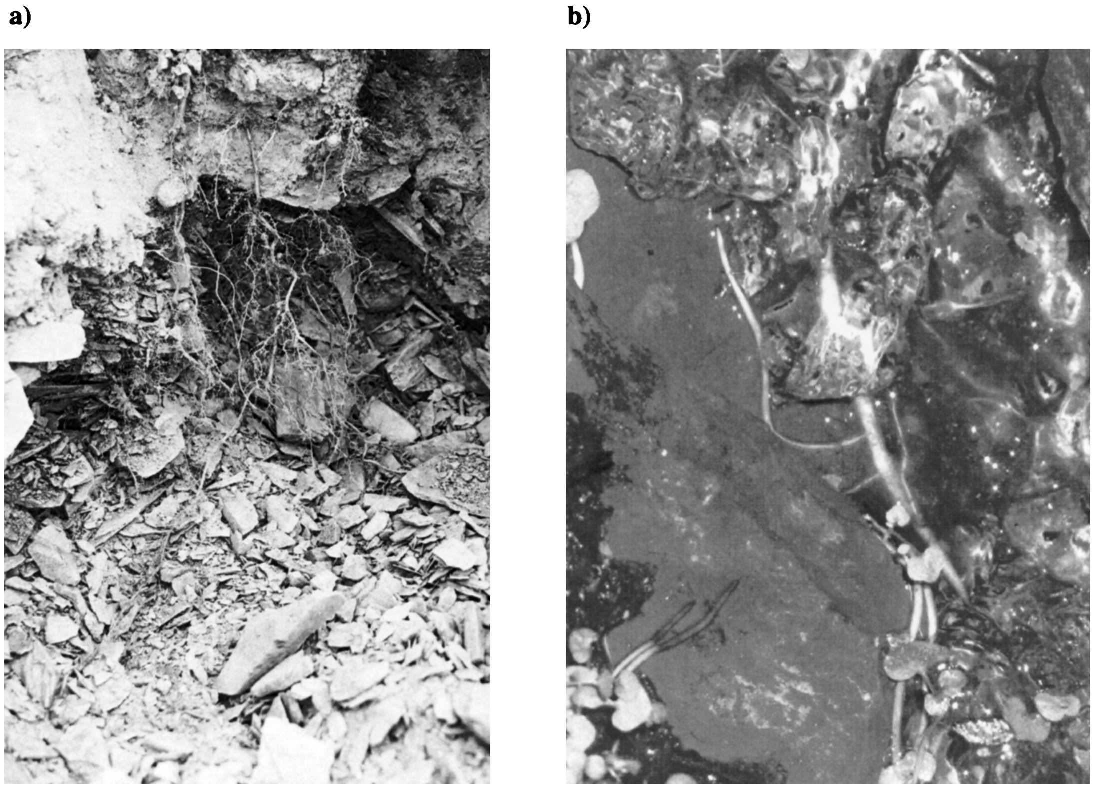

Fig. 5. Tree roots growing through (a) slate processing fines; root system 18 mo after planting, approximate image width 2 m (M. Nason) and (b) hydrogel; roots 12 mo after planting, approximate image width 0.1 m (E. Rowe).

plant nutrients per unit volume (Table 3) show that new hydrogel and SPF are both likely to be effective at retaining nutrients and preventing their loss through leaching. Neither material completely restricts plant nutrient availability, but hydrogel may reduce availability of NO_3^- and NH_4^+. This may explain the slower growth of some species with hydrogel, although if nitrogen were limiting one would expect a stronger effect on willow than on the N-fixing species and this is not the case (Fig. 2). The slower growth of Italian alder and the increased mortality of all species with hydrogel compared with SPF is more probably related to effects on water retention than on nutrient availability.

Placement of the hydrogel in the field in a dry state did not cause extra mortality in comparison with trees grown in its absence. While dry hydrogel will theoretically continue to withdraw water from the compost-filled planting bag until it has reached an equilibrium, which might imply a drop in water potential within the bag to below wilting point, in practice there is little capillary contact between the compost in the bag and the hydrogel until the latter has been wetted by rain. It would however be advantageous to apply hydrogel when a period of rain is expected.

For hydrogel to work effectively in the drought-prone environment of waste rock tips, tree roots would need to encounter fine particulate matter in the core of the tip within 18 mo after planting. Rapid root establishment is also essential in view of the growth and increasing water demand of the trees, which reduce the time for which the water in an isolated planting pocket can sustain the tree. This is necessary when using hydrogel because this material may rapidly become ineffective in the field, particularly if exposed to extremes of temperature or ultraviolet light. A severe reduction in its water-holding capacity was observed in the current study. Another problem, revealed by excavation of expired trees, was that much of the hydrogel had been washed, fallen, or otherwise moved into inaccessible positions within the blocky matrix. This happened despite the large grain size of the hydrogel, and might have been even more rapid had a finer grade of hydrogel been used. Retention of hydrogel or granular composts within the blocky matrix might be reduced by mixing with other materials, particularly fibrous composts or inert fibers.

The increased growth rates of trees achieved by adding fertilizer will lead to a more rapid exhaustion of the water resource, but benefits for root growth and penetration seem likely to outweigh this effect. In the current study, adequate amounts for the duration of the observation period of the major plant nutrients and trace elements were supplied in the controlled-release fertilizer, at least for the treatments with additional amendments. Analysis of the leaf phosphorus concentration in Italian alder 42 mo after planting revealed no difference between trees in the study and trees growing on deep fertile soil. Although it is possible that periods of nutrient deficiency occurred during the growth of the trees, the normal phosphorus concentrations in leaves, together with the failure of the nitrogen-fixing alders to outperform the nonfixing willows, suggest that nutrient deficiency was not a major cause of stress and mortality compared with water deficiency. However, such limitations would reduce growth at later stages of tree establishment. Nutrient availability could be increased by regular fertilizer additions (including trace elements), or by increasing the amount supplied initially. The buildup of organic matter from root and leaf material is also likely to be important for developing the capacity of the planting pocket to retain and supply nutrients for further tree growth.

Survival in the long term depends on the distribution of fine material deeper within the tip, and the severity of episodic drought. At this site on deep 50- to 100-yr-old slate tips, natural tree establishment at a low density [especially of silver birch (*Betula pendula* Roth) and *Salix* spp.] is observed, with its distribution clumped in areas with a higher concentration of fine slate particles at the surface. Where tips have been excavated, long roots from these trees penetrating at least 5 m vertically down through the tip have been observed. This suggests that blocky slate tips can sustain tree growth in the long term, provided that trees can be kept alive until they have reached a sufficient size for their roots to reach permanent sources of moisture.

Willow cuttings established rapidly, in terms of biomass growth (as indicated by shoot basal area) and crown height, showing that this cheap method of plant propagation can be effective for this species. However, growth of alder species was more rapid. Further investigation would be required to test whether this is related to the method of establishment or to the nitrogen-fixing capacity of the alders.

CONCLUSIONS

In contrast to previously unsuccessful restoration schemes, trees were successfully established on blocky quarry waste without mechanical alteration when SPF was added below the planting bag. However, pocket planting techniques still need to be improved if they are to be used widely and successfully. In such an extreme environment, approaches in which small numbers of trees are planted but more resources are invested in each one are likely to result in greater numbers of established trees than scattering larger numbers with less care. Such approaches are likely to be cheaper per tree successfully established, especially where fencing and other fixed site costs are substantial.

The poorer growth of trees planted without either SPF or hydrogel, and the near-complete mortality of trees planted without SPF, imply that discontinuity between the tree planting bag and the tip interior caused a shortage of water and nutrient resources. In the absence of SPF, such slowly-growing trees are less likely to survive long enough for their roots to grow into the tip interior. The extra growth of roots allowed by the hydrogel was not effective in preventing drought-induced mortality.

Localized pockets of SPF are likely to increase the continuity of water-holding material down into the blocky waste tip and provide channels for the growth of roots. Quarries with an overproduction of rock fines should therefore utilize this material as a resource for improving tree establishment, where access permits. The effectiveness of SPF may be increased further by blending it with compost, or other soil conditioning material. Hydrogel proved ineffective as an amendment in the long term, but if modified to reduce exposure to UV or extremes of temperature, the method may have some potential for less accessible sites. Hydrogel may be better used mixed with other lightweight materials, or in larger quantity. The success of pocket planting techniques on blocky waste depends on tree roots reaching sufficient water-holding material in the tip interior before the tree is killed by drought. This is made more likely by increasing the size and nutrient content of the planting pocket.

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