The establishment of some form of vegetation is a vital part of the restoration strategy for landfill sites in many parts of the world (Department of the Environment 1996; California Integrated Waste Management Board 1999; Environmental Protection Agency 1999; Office of Superfund Remediation and Technology Innovation 2006). The choice of vegetation is especially important because it affects the appearance of the site and the way it fits into the wider landscape. Early guidance issued by the U.K. Department of the Environment (Department of the Environment 1986) actively discouraged tree planting on capped landfill sites. Principal concerns have included 1) the perception that tree roots could penetrate through an engineered landfill cap, allowing water ingress or escape of landfill gas; 2) shallow rooting resulting from the presence of dense soil layers or cap material may lead to drought and windthrow susceptibility; and 3) woodland establishment might disrupt or compromise landfill pollution control measures if the trees were to blow over. In addition, tree survival and performance were considered to be adversely affected by many landfill site conditions.

The U.K. Forestry Commission Research Division (now Forest Research) conducted an extensive desk review of *The Potential for Woodland Establishment on Landfill Sites* in 1993 (Dobson and Moffat 1993), which evaluated the likely patterns of tree root growth on landfill sites, the ability of tree roots to penetrate a landfill mineral cap, whether trees on these sites would be at risk from windthrow, and whether trees can actually grow on the comparatively harsh conditions of the landfill environment. The findings of the 1993 study suggested that it was possible to establish trees on modern containment landfills provided the sites were engineered to a standard suitable for effective pollution control, the landfill cap was well compacted (bulk density greater than 1.8 g/cm³), and there was sufficient thickness of soil to prevent the threat of tree root penetration into the cap beneath.

However, the findings of the desk study were drawn from research not directly involving the landfill environment, because pre-1986 guidance had effectively prevented tree planting on recent landfill sites. The then Department of the Environment and its successors, now the Department of Communities and Local Government, has funded a program of study since 1993 to establish and monitor field experimental plots on landfills that had been constructed close to the specifications identified by Dobson and Moffat (1993). This article presents the results of the field-based experiments into tree performance monitoring on the five landfill sites, which have now been monitored for 10 years.

**MATERIALS AND METHODS**

A screening process was used to evaluate the characteristics of a large number of landfill sites identified by the Environmental Services Association and U.K. Waste Licensing Authorities. To select appropriate sites for the study, essential criteria were the presence of an engineered clay cap, an uncompacted soil cover with a minimum thickness of 1 m (3.3 ft), and a range of soil types and climatic conditions to be represented. The sites chosen were located at Bristol (Yanley), Swindon (Shaw Tip), Skelmersdale (Pimbo), Hatfield (Beech Farm), and Ely (Grunty Fen). Site locations and characteristics are summarized in Table 1.

Reclamation and woodland establishment practices at the sites followed, as closely as possible, the recommendations in *The Potential for Woodland Establishment on Landfill Sites* (Dobson and Moffat 1993). Most sites had soil or soil-forming materials placed by “loose tipping” (Bending et al. 1999) to reduce the risk of soil compaction, although ripping was used to alleviate compaction at Beech Farm. All sites except Shaw Tip were provided with some recycled topsoil material, although this was usually of limited thickness and of likely poor quality compared with standard definitions (British Standards Institution 1994).

Eight tree species were planted (total 1,152 trees) at each site in individual species plots of 36 trees. Species plots were replicated four times in a randomized block experimental design (Pearce 1976). Tree species were chosen from a list recommended by Dobson and Moffat (1993) with consideration given

---

**Key Words.** Landfill; nutrition; tree growth; tree species; tree survival.
Table 1. Details of the five experimental sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude and longitude</th>
<th>National grid reference</th>
<th>Altitude (m O.D.)</th>
<th>Annual rainfall (mm)</th>
<th>Soil thickness (m)</th>
<th>Altitude (m O.D.)</th>
<th>Annual rainfall (mm)</th>
<th>Soil thickness (m)</th>
<th>Altitude (m O.D.)</th>
<th>Annual rainfall (mm)</th>
<th>Soil thickness (m)</th>
<th>Altitude (m O.D.)</th>
<th>Annual rainfall (mm)</th>
<th>Soil thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beech Farm</td>
<td>51.78N, 0.26W</td>
<td>TL 200100</td>
<td>80</td>
<td>675</td>
<td>1.0</td>
<td>80</td>
<td>13</td>
<td>105</td>
<td>105</td>
<td>13</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>Grunty Fen</td>
<td>52.40N, 0.20E</td>
<td>TL 497798</td>
<td>12</td>
<td>550</td>
<td>1.0</td>
<td>12</td>
<td>12</td>
<td>105</td>
<td>105</td>
<td>13</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>Pimbo</td>
<td>53.53N, 2.74W</td>
<td>SD 512040</td>
<td>70</td>
<td>900</td>
<td>1.5</td>
<td>70</td>
<td>70</td>
<td>100</td>
<td>100</td>
<td>70</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td>Shaw Tip</td>
<td>51.57N, 1.83W</td>
<td>SU 122858</td>
<td>20</td>
<td>900</td>
<td>1.5</td>
<td>20</td>
<td>20</td>
<td>20</td>
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<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>Yanley</td>
<td>51.43N, 2.64W</td>
<td>ST 556698</td>
<td>0</td>
<td>900</td>
<td>1.5</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 2. Estimated tree survival probabilities after eight growing seasons (nine for beech at Shaw Tip).

<table>
<thead>
<tr>
<th>Species</th>
<th>Beech Farm survival</th>
<th>SE</th>
<th>Grunty Fen survival</th>
<th>SE</th>
<th>Pimbo survival</th>
<th>SE</th>
<th>Shaw Tip survival</th>
<th>SE</th>
<th>Yanley survival</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>0.86</td>
<td>0.068</td>
<td>0.014</td>
<td>0.068</td>
<td>0.88</td>
<td>0.065</td>
<td>0.98</td>
<td>0.024</td>
<td>0.66</td>
<td>0.093</td>
</tr>
<tr>
<td>Beech</td>
<td>0.81</td>
<td>0.076</td>
<td>0.81</td>
<td>0.076</td>
<td>0.81</td>
<td>0.076</td>
<td>0.81</td>
<td>0.076</td>
<td>0.81</td>
<td>0.076</td>
</tr>
<tr>
<td>Corsican pine</td>
<td>0.69</td>
<td>0.128</td>
<td>0.48</td>
<td>0.48</td>
<td>0.098</td>
<td>0.52</td>
<td>0.098</td>
<td>0.52</td>
<td>0.098</td>
<td>0.52</td>
</tr>
<tr>
<td>English oak</td>
<td>0.78</td>
<td>0.081</td>
<td>0.08</td>
<td>0.08</td>
<td>0.052</td>
<td>0.64</td>
<td>0.094</td>
<td>0.63</td>
<td>0.095</td>
<td>0.63</td>
</tr>
<tr>
<td>Hybrid larch</td>
<td>0.36</td>
<td>0.094</td>
<td>0.00</td>
<td>0.00</td>
<td>0.001</td>
<td>0.29</td>
<td>0.103</td>
<td>0.77</td>
<td>0.083</td>
<td>0.41</td>
</tr>
<tr>
<td>Italian alder</td>
<td>0.77</td>
<td>0.083</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.80</td>
<td>0.079</td>
<td>0.80</td>
<td>0.079</td>
<td>0.80</td>
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<tr>
<td>Leyland cypress</td>
<td>0.55</td>
<td>0.097</td>
<td>0.097</td>
<td>0.097</td>
<td>0.77</td>
<td>0.083</td>
<td>0.41</td>
<td>0.41</td>
<td>0.096</td>
<td>0.41</td>
</tr>
<tr>
<td>Norwegian maple</td>
<td>0.38</td>
<td>0.095</td>
<td>0.44</td>
<td>0.44</td>
<td>0.097</td>
<td>0.88</td>
<td>0.065</td>
<td>0.88</td>
<td>0.065</td>
<td>0.83</td>
</tr>
<tr>
<td>Silver maple</td>
<td>0.91</td>
<td>0.057</td>
<td>0.91</td>
<td>0.91</td>
<td>0.001</td>
<td>0.29</td>
<td>0.103</td>
<td>0.77</td>
<td>0.083</td>
<td>0.55</td>
</tr>
<tr>
<td>Whitebeam</td>
<td>0.41</td>
<td>0.096</td>
<td>0.55</td>
<td>0.55</td>
<td>0.097</td>
<td>0.88</td>
<td>0.065</td>
<td>0.88</td>
<td>0.065</td>
<td>0.83</td>
</tr>
<tr>
<td>Wild cherry</td>
<td>0.78</td>
<td>0.081</td>
<td>0.47</td>
<td>0.47</td>
<td>0.098</td>
<td>0.80</td>
<td>0.079</td>
<td>0.80</td>
<td>0.079</td>
<td>0.80</td>
</tr>
</tbody>
</table>

SE = standard error.
precise failure numbers. Tree height and growth increment were measured annually in the dormant season (November to March) between 1994 and 1999 and then every 2 years between 2000 and 2003. In the first 2 years of the experiment, all failed trees were replaced with new plants in the winter after a height assessment.

Yield class gives a clearer indication than tree height of how well a species is performing against the potential that it might...
attain at a given age assuming standard forestry practice (Edwards and Christie 1981). It is equivalent to site index as used in the United States and elsewhere. General yield class is based on the mean height of the 100 tallest trees in a stand (Rollinson 1991), but in this study, it was calculated for each species based on mean height data resulting from the inadequate number of measured trees in each plot. Because trees at Beech Farm were younger than 10 years, no yield class data were derived for this site.

Foliar samples were collected from each site in August (deciduous species) and November (evergreens) in 1998 and 2001 following standard procedures (Taylor 1991); a bulked sample was obtained from representative leaves or needles from five trees per plot. The samples were analyzed at the Forest Research Chemical Laboratories in Farnham, Surrey, U.K. Individual samples were ground and then digested with a mixture of sulphuric acid and hydrogen peroxide. Nitrogen and phosphorus concentrations were measured by colorimetry and base cations by plasma emission spectroscopy according to standard operating procedures established in the laboratory. Quality control was ensured by the inclusion of two certified reference materials (NCS DC73350 and DC3351 from the China National Analysis Center for Iron and Steel) in each batch of samples. The experimental plots were fertilized with nitrogen (as urea) at 150 kg N/ha (134 lb/acre) in April 1999 and April 2002. Fertilizer was applied in 1 m (3.3 ft) spots around each tree.

Because of the replacement of a few species at some sites in the first 2 years after the experiments began, an index of comparative survival was based on the number of live trees of each species at each site after eight growing seasons. This was analyzed statistically using a binomial generalized linear model with log link and a binomial denominator of 16. The exception was for beech at Shaw Tip where survival after 9 years was used because no observations were made at 8 years. Replacement trees were not included in the analysis. Tree heights at Year 8 were log-transformed to stabilize the variance, and the log-transformed heights were analyzed using a general linear model. Analysis was based on the trees planted at the beginning of the experiments, and replacement trees were not included. For both survival and height comparison, there were no significant differences between experiment blocks and so site mean tree species values were used in subsequent analysis and evaluation. All statistical analyses were undertaken using Genstat version 8.1 (GenStat 2005).

RESULTS AND DISCUSSION

Survival

Table 2 shows estimated tree survival probabilities and their standard errors after eight (nine) growing seasons, and Figure 1 shows the change in survival rate since planting based on the original stock. The species by site interaction was significant ($P < 0.001$). The calendar year was not significant, indicating that data were comparable despite some species being planted a year or two apart from the others. Considering the range of species, overall tree survival performance was best at Shaw Tip and worst at Grunty Fen. Most sites showed an initial decline in the total number of trees of each species that tended to stabilize with time. Compared with the traditional guidance of approximately 80% for acceptable stocking density of new closely spaced plantations on greenfield sites (Hart 1991), survival has been broadly acceptable for woodland establishment at most sites and for most tree species. This suggests that site preparation, tree planting operations, and silvicultural care have been suitable for the purpose of establishing trees on the experimental plots.

There was no indication of group dieback resulting from landfill gas within the soil cover at any site, and the early decline in tree numbers at some sites is likely to reflect soil drainage conditions or quality of planting stock rather than possible effects of landfill gas or heat (Moffat and Houston 1991). Differences in survival rates between species over the longer term may be explained by the general tolerance of the different species to specific site conditions. Hence, at Shaw Tip, the survival rate stabilized within 2 years of planting, whereas at Pimbo, some species showed a continued decline in numbers, which may be related to their inability to tolerate site conditions. The poor survival at Grunty Fen is probably the result of the small available water capacity of the clayey planting medium (estimated at 13% by volume [Hodgson 1976]) combined with the high soil moisture deficit experienced at the site, which is situated in the driest part of the country. The mean maximum potential soil moisture deficit (PSMD) between 1994 and 2004 at Broom's Barn 30 km (18 mi) east southeast of Grunty Fen was almost 250 mm (10 in), and maximum PSMD ranged between 280 and 430 mm (11.2 and 17.2 in) in the first 5 years.

Species that showed consistently good survival performance across most of the sites included ash, whitebeam, white poplar, and wild cherry (Table 2). All species at Shaw Tip, with the

### Table 3. Predicted means of log tree height (m) after eight growing seasons (nine for beech at Shaw Tip).

<table>
<thead>
<tr>
<th>Species</th>
<th>Beech Farm mean</th>
<th>Beech Farm SE</th>
<th>Grunty Fen mean</th>
<th>Grunty Fen SE</th>
<th>Pimbo mean</th>
<th>Pimbo SE</th>
<th>Shaw Tip mean</th>
<th>Shaw Tip SE</th>
<th>Yanley mean</th>
<th>Yanley SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>5.55</td>
<td>0.171</td>
<td>4.1</td>
<td>0.197</td>
<td>5.84</td>
<td>0.171</td>
<td>6.22</td>
<td>0.171</td>
<td>5.66</td>
<td>0.171</td>
</tr>
<tr>
<td>Beech</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.90</td>
<td>0.171</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corsican pine</td>
<td>5.81</td>
<td>0.241</td>
<td>4.65</td>
<td>0.171</td>
<td>5.34</td>
<td>0.171</td>
<td></td>
<td>5.23</td>
<td>0.171</td>
<td></td>
</tr>
<tr>
<td>English oak</td>
<td>5.35</td>
<td>0.171</td>
<td>4.71</td>
<td>0.341</td>
<td>5.43</td>
<td>0.171</td>
<td></td>
<td>5.00</td>
<td>0.171</td>
<td></td>
</tr>
<tr>
<td>Hybrid larch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.83</td>
<td>0.197</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italian alder</td>
<td>6.37</td>
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<td></td>
<td></td>
<td>6.54</td>
<td>0.171</td>
<td>6.32</td>
<td>0.171</td>
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<tr>
<td>Leyland cypress</td>
<td>6.35</td>
<td>0.171</td>
<td></td>
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<td>6.35</td>
<td>0.171</td>
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<td>5.74</td>
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<tr>
<td>Silver maple</td>
<td></td>
<td></td>
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<tr>
<td>Sycamore</td>
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<td>5.89</td>
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<td>0.171</td>
<td>6.55</td>
<td>0.171</td>
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<td>0.171</td>
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<tr>
<td>Whitebeam</td>
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<td>0.171</td>
<td>4.56</td>
<td>0.171</td>
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</tbody>
</table>

SE = standard error.

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exception of Leyland cypress, maintained survival rates in excess of 70% of the original numbers planted. Ash and wild cherry demonstrated good survival performance under the relatively wet conditions at Pimbo, whereas English oak and ash at the Yanley and Beech Farm sites and Norway maple at Beech Farm also retained a high survival rate. Apart from whitebeam, most species at Grunty Fen declined over the 10-year period and only white poplar showed signs of stabilizing at a survival rate of approximately 55% by 2003. Species that performed very poorly at the low rainfall Grunty Fen site included Japanese larch, Italian alder, English oak, and ash. The poor survival of original trees of Italian alder and wild cherry at Yanley and white poplar, Italian alder, and Corsican pine at Beech Farm was caused by deer browsing.

Figure 2. Mean annual tree height increments at the five landfill sites since planting. Note: The legend for Beech Farm is different from the other four sites.
Growth
Tree growth was evaluated by means of annual measurements of height from 1994 to 1999 and on a 2-year basis from 2000 onward, except at Beech Farm where annual observations were continued until 2001 as a result of replanting of the experiment. Table 3 contains the predicted means of log tree height at age 8 years (9 years). The species by site interaction was again significant (P < 0.001) and, similar to the survival analysis, the year of planting was not. Figure 2 shows the mean annual increment and height for each of the species at each site. It shows that Shaw Tip produced the fastest height growth rates for most species and that the slowest tree growth occurred at Grunty Fen. Across all sites, height growth rates were greatest in the poplar, alder, cherry, whitebeam, and ash species. Species with slow absolute growth rates included beech, sycamore, and oak, although care must be exercised in making comparisons among species with different growth habits.

Growth increments did not show steady annual increases and the performance of individual species planted at different sites was also markedly variable. This probably reflects different climatic or site conditions such as soil moisture or nutrient status in different years. However, annual increments of most species at Grunty Fen appeared to be suppressed compared with the other sites, especially between 1994 and 1999, and tree growth rate has showed little tendency to accelerate in more recent years at this site.

Most species reached their maximum annual increment in 2000 to 2001 or in 2002 to 2003 (Table 4), which may reflect, in part, the fertilizer applications in 1999 and 2002. Annual rainfall data from three meteorological stations within reasonable proximity to Yanley (Long Ashton), Shaw Tip (Oxford), and Pimbo (Bradford) indicate that 1995 to 1996 were relatively dry years, which may help to explain the small increments in annual growth rate during this period. It is also possible that tree growth responded to the upturn in annual rainfall between 1997 and 2000. Summer drought in 1995 was very pronounced at all sites, which probably explains why such poor height increments were experienced in the subsequent growth period.

Nutrition
Taylor (1991) gives foliar nitrogen (N), phosphorus (P), and potassium (K) concentrations that are regarded as representing deficient and optimal conditions for the more common species in British forestry. For the remaining species, information from Auchmoody and Smith (1977), Callan and Westcott (1996), and Ystaas and Froynes (1997) was used to estimate deficient and optimal values. The appropriate values for optimum and deficient N, P, and K status are presented in Table 5 together with an assessment of the status of each of the tree species at each of the five sites. The results demonstrate that N deficiency was widespread with most species demonstrating severe deficiency at two or more sites. Only white poplar and Italian alder demonstrated optimal N status at some sites. These results generally agree with the growth data discussed previously and may explain the reduced growth rate in some species in 2000 to 2001. Italian alder might be expected to show less of a N deficiency than other species because of its N-fixing capability when infected with the actinomycete Frankia. However, it is possible that at some sites, trees were poorly nodulated, impairing their ability to fix N. When reapplication of N fertilizer was made in Spring 2002, the maximum annual increment in 2002 to 2003 was identified in some species (Table 4), which might be attributed to this addition.

Phosphorus and K were generally optimal in whitebeam, sycamore, poplar, cherry, and ash but showed some deficiency in other species. Corsican pine was deficient in P and K at most sites. Oak and beech also exhibited slight or moderate deficiencies in K. The foliar data confirm that K supply is generally not a problem for woodland establishment on brownfield land (Moffat and McNell 1994).

In 1998, of the 37 combinations of species and site investigated, only three, alder at Shaw Tip and poplar at Pimbo and Beech Farm, were considered to have optimal nutrient supply (Kennedy and Moffat 1999). In 2001, only four had optimal supply of all three nutrients despite a N application in Spring 1999; species include poplar at Pimbo, Shaw Tip, and Yanley and Italian alder at Y anley. The deficiencies identified in the 2001 foliar analysis demonstrate the lack of impact longevity of the applied N fertilizer. It is possible that considerable leaching of N occurred in the soil materials used, most of which contained little organic matter. Reclamation using these materials in 1993 to 1994 predated guidance on soil-forming materials (Bending et al. 1999), which strongly advocated the use of organic wastes to build up fertility and nutrient-holding capacity of the substrates. Experience from this study would appear to confirm the applicability of this guidance, because supplementary fertilizer application was required only 3 years after the first application.
liance on the regular and continued application of mineral fertilizer to maintain stand growth and condition does not support sustainability principles and is a drain on maintenance budgets. Instead, sites should be prepared with amendments of organic waste materials if soil-forming materials are used for reclamation purposes.

**Table 5. Foliar nutrient status at the experimental sites in 1998 and 2001.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
<td>Beech</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
<td>Corsican pine</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
<td>English oak</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
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<td>NA</td>
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<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
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<td>Italian alder</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
<td>Leyland cypress</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
<td>Silver maple</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;2.0</td>
<td>&gt;2.3</td>
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<tr>
<td>Whitebeam</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>&lt;2.0</td>
<td>&gt;2.3</td>
</tr>
<tr>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>&gt;2.3</td>
</tr>
<tr>
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<td>NA</td>
<td>NA</td>
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<td>&lt;2.0</td>
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</table>

Comparison with Trees on Other Landfill and Greenfield Sites

Rawlinson et al. (2004) found that of 21 species tested experimentally, native and broadleaved species were most successful after 3 years. Handel and McLoughlin (2006) also suggested that native species can flourish on properly restored landfills. In con-

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trast, Dobson and Moffat (1993) reviewed the results of tree
growth on 19 restored landfill sites and found considerable varia-
tion in the performance of different species, both native and
nonnative, coniferous and broadleaved. This study has also
found that nonnatives performed well on some sites but not
others; there appears to be no universal truth in this respect.
Instead, simple analysis of the performance of individual species
over a 10-year period suggests that soil and site characteristics
such as climate are very important. Like Rawlinson et al. (2004),
we found conifers to perform badly, but this is probably the
result of the alkaline nature of the soil substrates at almost all the
experimental sites.

Table 6 presents the yield class for selected species at Year 10
compared with regional averages derived from data from forests
and woodlands on undisturbed land. The results confirm the
relatively poor performance of trees at Grunty Fen and the
impressive growth at Shaw Tip. The conifers naturally demon-
strate a larger yield class than the broadleaves, and growth was
better than average at Shaw Tip and Pimbo. Of the broadleaves,
oak showed consistent growth closest to average expectations,
although with only one or two exceptions (e.g., ash at Grunty
Fen and sycamore at Yanley), growth of broadleaved species
was reasonable given the comparatively hostile conditions at
most sites.

Implications for Woodland Establishment on
Landfill Sites
Taken together, the 10 years of monitoring field experiments on
modern landfill sites suggest that it is possible to establish wood-
land composed of tree species that grow reasonably well com-
pared with equivalents established on greenfield sites. From an
engineering standpoint, the results reinforce the need for uncom-
pacted, rootable soil or soil-forming material, preferably placed
by loose tipping or complete cultivation. The widespread N
deficiency detected during the monitoring program was predict-
able given the relatively infertile materials used in restoration at
most sites (Table 1). However, there was no opportunity to use
organic waste materials such as sewage sludge or composts as an
overall treatment to the sites. The inability of artificial mineral
fertilizers to redress permanent nutrient deficiency in the field
experiments underlines the need for alternatives such as organic
amendments, which are often a more effective approach to re-
store land amendment (Bending et al. 1999; Moffat 2006).

Proper attention to provision of a suitable thickness of soil or
soil-forming material, prevention of compaction, and site fertili-
ity can maximize the likelihood of good tree performance. How-
ever, there was some evidence from the field experimentation
program that regional rainfall, or lack of it, was also important.
For some parts of the country, notably the drier south and east,
meticulous weed control is increasingly necessary, but even if
undertaken according to good forestry practice, there remains a
risk to tree survival and performance on those sites where plant-
available water may be limited, for example at Grunty Fen where
low rainfall combined with a clayey substrate of low available
water capacity. The potential influence of climate change has
been appreciated in recent guidance on suitable soil provision for
landfill and other restored brownfield sites (Moffat 1995), but
further work is needed to refine this in the light of government-
predicted climate change scenarios (Hulme et al. 2002).

Considered species selection is an obvious way to maximize
the likelihood of a successful woodland, and the field experi-
mental program has demonstrated that some tree species tested
are more robust and/or provide a low risk of failure. These have
been discussed in this article. Other tree species, especially Ley-
land cypress, Japanese larch, and Norway maple, performed very
poorly during the experiment and should be chosen with care in
future schemes on similar sites. The basic maxim is to match
species to site conditions as much as possible and to be conser-
vote in the expectations for the new woodland, e.g., not to
expect tree species typical of natural woodland to thrive on unam-
ended soil-forming materials, but to choose so-called pioneer
species like poplars and alders, which are comparatively tolerant
of infertility and exposure.

However, climate change makes it more difficult to be certain
about choice of species because the climate in future years is
likely to be significantly different than today, especially in the
south and east of the British Isles (Broadmeadow et al. 2004). In
these regions, notably drought-tolerant species should be chosen.
Some species such as white poplar may perform well as a re-
response to climate change (Cannell et al. 1989), but others such as
cherry may fare less well than today. It may also be necessary to
consider species not tested in these experiments such as walnut

| Table 6. Measured and regional average general yield classes (m³/ha/year) at Year 10 for all sites except Beech Farm.² |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Species         | Measured        | Regional        | Measured        | Regional        | Measured        | Regional        |
|                 | Grunty Fen      | average         | Pimbo           | average         | Shaw Tip        | average         |
| Ash             | 2               | 5               | 8               | NA              | 10              | 5               |
| Beech           | 4               |                  | 5               | 8               | 10              | 5               |
| Corsican pine   | 6               | 15              | 16              | 14              | 12              | 16              |
| English oak     | 4               | 5               | 8               | 7               | 6               | 5               |
| Hybrid larch    | 12              | 11              | 12              | 11              | 12              | 11              |
| Italian alder   | NA              | NA              | 12              | 12              | 12              | NA              |
| Leyland cypress | 24              | 15              | 24              | 15              | 24              | 15              |
| Silver maple    | 10              | 7               | 10              | 7               | 10              | 7               |
| Sycamore        | NA              | 4               | 6               | 4               | 6               | 4               |
| Whitebeam       | 4               | NA              | 6               | NA              | 8               | NA              |
| White poplar    | 4               | NA              | 4               | 6               | 6               | 6               |
| Wild cherry     | 2               | 5               | 6               | 10              | 6               | 10              |

²General yield class is expressed in terms of the maximum annual increment of cumulative stem volume per hectare for a given species assuming a standard management regime.
NA = yield class curves not available (trees less than 10 years old) for these species.
(Juglans nigra L.), holm oak (Quercus ilex L.), Eucalyptus spp., and Nothofagus spp. Such species are, of course, nonnative to the British Isles.

Of the species tested and found to be relatively successful, some caution should be exercised on mineral-capped landfills if selecting poplar and alder species. Bending and Moffat (1997) found that poplar roots were effective in penetrating clay compacted to levels required of mineral caps (greater than 1.8 g/cm; 15.0 lb gallon−1), and Hutchings et al. (2001, 2006) obtained similar results for alder species on a containment landfill in Hertfordshire. These species are relatively tolerant of soil anaerobism and might be expected to pose a risk of root penetration on landfills where the cap suffers from weakness in its fabric and/or is unprotected by an artificial capping layer. The likelihood of downward root growth toward and potentially into the landfill cap environment is expected to become more complex as the trees grow and mature and begin to encounter further limitations to growth. The five experiments are thus a valuable resource as a means of monitoring species tolerance and performance on landfill sites over time and as a potential source of material on which to study root/landfill cap interactions in the future. More reliable information on both these issues will become available as the monitoring plots mature.

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LITERATURE CITED


Young sweet cherry trees respond favourably to phosphorus fertilization. Acta Horticulturae 448: 383–388.

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Résumé. Une série d’expériences ont été mises au point en Angleterre au début des années 90 sur cinq sites fermés de dépôt de matières qui ont été conçus selon des normes modernes d’ingénierie, et ce afin de tester la performance relative de 14 espèces forestières indigènes et non indigènes. Cet article décrit les résultats du suivi de leur taux de survie, de croissance et de nutrition sur une période de 10 ans. Les expériences ont démontré que la plupart des espèces, notamment le frêne, le sorbier, le peuplier blanc et le cerisier sauvage peuvent généralement s’établir sur des sites de dépôt avec des taux de survie comparables aux autres types de sites. En dépôt de l’infertilité générale du site, la croissance de plusieurs espèces d’arbres – par exemple le frêne, le hêtre, le chêne anglais, le sycamore, l’auleine italienne, l’érable argenté, le peuplier blanc et le sorbier – était similaire à celle attendue au sein d’espaces verts situés dans la localité où le site de dépôt était situé. Tout comme l’infertilité, la sécheresse du sol et le broutage par les mammifères ont été identifiés comme limitant la performance des arbres de certaines espèces, en particulier sur certains sites. Après 10 ans, il n’y avait pas d’indice évident d’interaction entre les systèmes de confinement du dépôt et les gaz provenant du dépôt.


Resumen. En los 90s, se llevaron a cabo una serie de experimentos en Inglaterra, en cinco sitios preparados con estándares modernos, para probar la respuesta relativa de catorce especies de árboles nativos y exóticos. Este reporte describe los resultados del monitoreo de su supervivencia, crecimiento y nutrición en un periodo de diez años. Los experimentos demostraron que varias especies, notablemente encino, chopo blanco y cerezo silvestre pueden ser establecidos comúnmente en sitios de relleno con tasas de supervivencia comparables a otros lugares. A pesar de la infertilidad general del sitio, el crecimiento de muchas especies de árboles (por ejemplo fresno, haya, encino inglés, sicomoro, aliso italiano, maple y chopo blanco) fue similar al esperado en sitios silvestres. Así también, la infertilidad, la resequedad del suelo y el ramoneo fueron identificados como limitantes para los árboles de especies particulares en algunos sitios. Después de diez años, no hubo evidencia de la interacción con los sistemas de contenedor o rellenos con gas.