Woodland establishment on landfill sites: site monitoring

On 5th May 2006 the responsibilities of the Office of the Deputy Prime Minister (ODPM) transferred to the Department for Communities and Local Government.

Department for Communities and Local Government
Eland House
Bressenden Place
London SW1E 5DU
Telephone: 020 7944 4400
Website: www.communities.gov.uk

This publication is only available online via the Communities and Local Government website: www.communities.gov.uk

Alternative formats under Disability Discrimination Act (DDA):if you require this publication in an alternative format please email alternativeformats@communities.gsi.gov.uk

Publication title: Woodland establishment on landfill sites: site monitoring
Date published: December 2000
Price: Free (web only)

Summary

This publication is the third in a series of reports concerning research on tree establishment and performance on landfill sites commissioned by the Department.

Order

This publication is only available online - see below.

Alternative formats under Disability Discrimination Act (DDA): if you require this publication in an alternative format (eg Braille or audio) please email alternativeformats@communities.gsi.gov.uk quoting the title and product code/ISBN of the publication, and your address and telephone number.

Acknowledgements

This study was funded by the Department of the Environment, Transport and the Regions with a financial contribution from Forest Research. We are particularly grateful to Dr T Simpson (Chairman) and Mr R Orpin (Nominated Officer) of the Minerals and Waste Planning Division. We must also thank the Steering Committee for their support and helpful guidance: Mr B Freeland (DETR secretary), Mr P E Gawn (Independent Consultant), Mrs E Simmons (formerly National Land Reclamation Panel), Mr R. Romans (Local Government Association), Mr C Anniss (Swindon Borough Council), Mr S Redwood (Quarry Products Association), Mr I Lanyon (Quarry Products Association), Mr P Annett (DETR Rural Development Division), Ms J Thomas (Environment Agency) and Dr G Wilson (Environmental Services Association).

We wish to thank the landowners and landfill operators who continued to support the experimental study of tree growth on their land. We wish to acknowledge the work by the Technical Support Unit of Forest Research, who maintained and monitored the five field experiments. In addition, we are grateful to Robert Brett & Sons Ltd for permission to perform the study at Waterford pit. Christopher French and Joanne Edgerton (Forest Research) gave invaluable help in the field and laboratory. Rob Kemp and Jerry Lee (Royal Holloway and Bedford New College, University of London) made the thin sections.

Go to table of contents

Preface

This publication is the third in a series of reports concerning research on tree establishment and performance on landfill sites commissioned by the Department of the Environment, Transport and the Regions. The third phase of research follows publication of the report *The potential for woodland establishment on landfill sites* (Dobson and Moffat, 1993) and *Tree establishment on landfill sites. Research and updated guidance* (Bending and Moffat, 1997). It describes the continuation of tree performance monitoring on experimental plots set up on five landfills during the second research phase. In addition, the study of the rooting habits of three tree species on a clay capped containment landfill is described.

The findings and recommendations in this report are those of the consultant authors and do not necessarily represent the views or proposed policies of Communities and Local Government.

Go to table of contents

Executive Summary

Past guidance issued by the Department of the Environment (1986) discouraged the planting of tree species on landfill sites. Accepting that this view was based on little scientific evidence, the Department commissioned Forest Research to undertake a desktop investigation into the potential for woodland establishment on landfills (Dobson and Moffat, 1993) followed by practical field and nursery-based research (Bending and Moffat, 1997). These studies suggested that provided certain standards are adhered to (especially the provision of 1.5 m of soil or soil-forming material overlying a mineral cap engineered to a bulk density of 1.8 g cm^{-3} or more), trees can be established on landfills without posing a threat to cap integrity.

This report gives details of two research projects designed to investigate root/cap interactions following woodland planting on landfills that have been constructed to (or close to) the standards identified in the previous research phases.

In 1994, experimental tree species plots were set up on five modern clay capped landfills across England, following the proposed standards for tree establishment (Section 2). At most sites the trees are now six years old. The experiment has provided useful early insights into the tree species most tolerant of site conditions on landfills. These include poplar, alder, cherry, whitebeam, oak and, where moisture deficits are moderate, ash. As yet, few conclusions can be drawn concerning root/cap interactions except that there is no indication that landfill gas pollution has occurred in the root zone above the cap, i.e. no sudden die-back has been observed. The experimental plots will continue to be maintained and monitored so that studies of tree root architecture over the landfill cap can be conducted in due course.

Excavations carried out at Waterford landfill site (Section 3), 10 years after tree planting, support the contention that if landfills are constructed following modern guidance the risk posed to cap integrity is minimal. No tree roots were observed to have penetrated the surface of the cap if at least 1.2 m of soil cover was placed over the cap. However, limited root penetration into the mineral cap was found where soil thickness was less than this. The tolerance of alder and poplar roots to anaerobic conditions is discussed, but it is unlikely that they will penetrate through a cap to the extent that landfill gas can escape or water can enter the landfill.

Go to table of contents

List of photographs (available to download below)

1. Landfilling operations at Yanley landfill site

2. Cultivation of loose tipped soil materials at Pimbo landfill site

3. Tree planting at Shaw landfill site in 1994

4. Ash at Shaw landfill site, July 2000. Length of yellow pole is 2 metres

5. View of woodland establishment at Shaw landfill site in 2000

6. Excavation of tree roots at Waterford

7. Example of root identification in a soil inspection pit at Waterford

8. Alder root behaviour at the soil/landfill cap interface at Waterford

Go to table of contents

1.0 Introduction

The acceptance of establishing trees on landfill sites depends primarily on the long term sustainability of landfill capping systems. Past guidance issued by the Department of the Environment (1986) actively discouraged the planting of tree species on landfill sites. The reasons given for such guidance were:

- the perception that tree roots could penetrate through an engineered cap and would thus compromise control of water ingress into the waste and allow the escape of landfill gas,
- the possibility that shallow rooting trees on landfill sites could increase the risk of trees blowing over, thus disrupting pollution control measures, and
- the observation that conditions on landfill sites could adversely affect tree survival.

The Department of the Environment later reconsidered this view, having acknowledged that it was based on little scientific evidence and field experience. In 1991, Forest Research, an agency of the Forestry Commission, was commissioned to evaluate, as a desk-top exercise, the potential for woodland establishment on landfill sites. A comprehensive review of relevant information was undertaken to enable well-founded guidance to be issued on all aspects of woodland establishment on landfill sites. In 1993, the final contract report was published as *The Potential for Woodland Establishment on Landfill Sites* (Dobson and Moffat, 1993). This evaluated:

- the ability of tree roots to penetrate a landfill cap,
- the ability of trees to dry out and cause desiccation cracking in a clay cap,
- whether trees on landfill sites would be at risk from windthrow, and
- whether trees can actually grow on the comparatively harsh environment of a landfill site.

The research suggested that

- landfill gas, leachate and high temperatures can all affect tree performance, but that these factors should not be important issues on well engineered containment landfill sites. Soil compaction, waterlogging, drought and other soil limitations were more likely to limit tree growth, but could be countered by adherence to proper reclamation standards,
- trees are generally shallow-rooted, with approximately 90% of roots in the upper 1 m of soil. Roots are mainly inhibited from exploring deeper depths by lack of oxygen and soil compaction. Such features are found in landfill clay caps engineered to modern specifications,
- trees growing on landfills with a depth of rootable soil of 1 m or more are no more susceptible to windthrow than trees on undisturbed sites. Techniques are available to

quantify the risk of windthrow,

- tree roots are not able to remove more water from compact clay than other types of vegetation, and the amount they can withdraw is unlikely to cause desiccation cracking,
- on modern well engineered containment landfills, trees could successfully be established without posing a threat to cap integrity. However, certain critical parameters were recognised if prevention of root penetration into the cap, and thus a standard suitable for effective pollution control, was to be maintained (Table 1.0).

Table 1.0. Landfill reclamation standards for a woodland after-use.

Critical Properties
Landfills should be sealed with an engineered low permeability cap
At least 1.5 m of soil or soil-forming material should be placed over a clay cap; at least 1.0 m over a synthetic cap
Soil materials should be loose tipped using dump truck and spread with excavator
Ideally, landfill should have slopes of 1 in 10 or steeper
Tree planting should be delayed if settlement of the cap and soil cover is likely to be severe
Tree species must be matched to particular site conditions
Silvicultural care during the aftercare period must be of a high standard

The publication of the report produced considerable interest in the landfill industry. In order to evaluate the recommendations made in the desk exercise, Forest Research was commissioned to undertake further research. This evaluated the guidance issued on cap construction, hydrological implications, and species selection using both field and pot trials. The second report (Bending and Moffat, 1997) confirmed the findings of the first report that trees could be established on modern landfills in such a way as to prevent damage to pollution control systems. It also recognised the following points:

- the planting of tree species, eg poplar, which are especially tolerant of anaerobic conditions, should be considered carefully on landfills which possess a single clay cap system. The roots of this genus appear able to penetrate compact clay, though only along planes of weakness, and might thus compromise the integrity of a poorly compacted cap,
- geological clays varied in their resistance to root penetration. Some types may be more suitable for cap construction on landfills where trees are to be planted than others, and
- composite landfill capping systems are likely to provide a greater safety factor than simple compact mineral barriers.

Concerns that tree roots could extract sufficient soil moisture to cause the shrinkage and cracking of the landfill cap were also allayed by a detailed study of water abstraction under a mature woodland located on a clay soil type.

The field trials set up during the second phase of the research project were established to demonstrate the application of reclamation recommendations on woodland establishment on landfill sites made in the first report (Dobson and Moffat, 1993). In addition, the trials would facilitate the study of tree root / landfill cap interactions at a later date when the trees were sufficiently mature. Section 2 of this report gives an update on the tree performance at the five sites, though the growth results must be regarded as interim in nature because the trees are still very young.

It was appreciated that the field trials would not yield results for at least ten years after planting, to allow tree root systems to develop to a size where excavation would yield useful results. In the interim, the Department of the Environment commissioned a study of tree rooting on a landfill site where trees had been planted in 1986, and where restoration practice had been close to modern guidance (Dobson and Moffat, 1993). Section 3 of this report describes the research in detail.

Go to table of contents

2.0 Long term monitoring plots on containment landfills

2.1 Introduction

The importance of setting up experimental sites specifically designed to investigate root / landfill cap interactions was recognised during the first phase of the landfill research project (Dobson and Moffat, 1993). Thus, in 1994 the Department of the Environment awarded Forest Research a three year contract to establish five experimental plots on landfills which had been constructed close to the specifications identified in Dobson and Moffat (1993). The results of tree performance at these sites were reported by Bending and Moffat (1997) for the first three years (1994-1997). Due to the need to monitor and maintain the plots through to maturity, a further contract was awarded in April 1997 to continue the work for an additional three years. This report is the final report of this contract and includes (for most sites) details of growth and survival after the sixth growing season.

The five landfills were chosen to reflect a range of site conditions in terms of fill composition, climate and soil type. The sites chosen were located at Bristol (Yanley) (See Photograph 1 below), Swindon (Shaw), Skelmersdale (Pimbo), Hatfield (Beech Farm) and Ely (Grunty Fen). The locations of the sites are shown in Figure 2.1.

Figure 2.1: Experimental tree species sites (available to download below)

Table 2.1 summarises the characteristics of each experimental site. The nature and quality of the materials used in the restoration of the plots varied widely. At Beech Farm, Yanley and Grunty Fen, the indigenous topsoil had been used. A mixture of topsoils imported into the site were used at Pimbo, whilst at Shaw a lime-rich soil-forming material, locally known as Coral Rag, was used. Soil materials were loose tipped, or recultivated using an excavator bucket (complete cultivation) to 1.0 m depth (See Photograph 2 below) Soil pH was neutral or slightly alkaline at all sites except Shaw which was moderately alkaline.

At each site, the experiments were laid out as a standard forestry research design with eight species planted in four replicates. As far as was practicable, the same tree species were used for all experiments. However, the relatively high pH at Shaw necessitated the use of alkali tolerant species. Further details on the experiment are given by Bending and Moffat (1997).

Table 2.1. Details of the five experimental sites

	Shaw Tip	**Pimbo**	**Yanley**	**Beech Farm**	**Grunty Fen**
Owner of site	Thamesdown Borough Council	Lancashire County Council	Terry Adams Ltd	RMC Aggregates (Greater London) Ltd	East Waste Ltd
National grid ref.	SU 122858	SD 512040	ST 556698	TL 200100	TL 497798
Altitude	100	105	20	80	13

(M.O.D.)					
Annual rainfall (mm)	700	900	900	675	550
Soil materials	Coral Rag limestone	Imported, various	100 mm topsoil over Keuper Marl	Sandy loam topsoil and subsoil	300 mm clay topsoil over clay subsoil
Ground preparation	Loose tipping	Loose tipping	Complete cultivation to 1.0 m using excavator	Complete cultivation to 1.0 m using excavator	Complete cultivation to 1.0 m using excavator
Soil thickness (m)	1.5	1.5	1.5	1	1
Soil pH	8.3	8.0-8.7	8.0-8.3	6.9-7.2	7.3-8.1
Year trees planted	1994	1994	1994	1993/96	1994

2.2 Management

Throughout the six year period the sites have been maintained following standard forestry practice. All the experimental plots were fenced to reduce browsing by rabbits and deer (See Photograph 3 below). Beating up (the replacement of lost trees) was carried out during the first three years and weed control has been undertaken once or twice per year depending on need. As the overall purpose of the contract was to investigate the possibility of tree root interactions with the landfill cap, additional management was undertaken to promote as much growth as possible. Weed control is usually stopped three to four years after tree planting, but it was continued throughout the six years. The sites were also fertilised with nitrogen fertiliser in April 1999 (see Section 2.5). Fence maintenance was undertaken at Shaw Tip and Pimbo.

Early tree performance at Beech Farm was disappointing and excavation revealed soil compaction below the topsoil which prevented root penetration and exploitation (Bending and Moffat, 1997). The site was totally cultivated using an excavator to 1 m depth in Autumn 1995, before replanting at the end of the year.

2.3 Tree survival

Bending and Moffat (1997) reviewed the first three years growth at the experimental plots. Figure 2.2 gives the tree survival results for 1997, 1998 and 1999. In general, survival has been above acceptable levels for woodland establishment at most sites and for most tree species (see endnote 1). This suggests that site preparation, tree planting operations and silvicultural care have been suitable for the purpose of establishing species plots. Across species, survival has remained greatest at Shaw Tip and worst at Grunty Fen. The poor survival at Grunty Fen is probably due to the small available water capacity of the planting medium, combined with the high soil moisture deficit experienced in the east of the UK. It is likely that the species with poorer survival at Pimbo (pine, oak and larch) were unsuited to the exposed position of the site. The low survival of Italian alder at Yanley and Beech Farm has been attributed to deer browsing.

Figure 2.2: Survival at the five sites since 1997 (available to download below)

2.4 Tree growth

Tree growth has been evaluated by means of annual measurements of height growth. This is a commonplace method for assessing growth, especially for young trees. Nevertheless, care must be exercised in comparisons between species with different growing habits. Bending and Moffat (1997) discussed the first three years height data in some detail. Figure 2.3 shows the growth achieved at each of the sites after 6 years. Poplar, alder, cherry, whitebeam and ash (See Photograph 4, .pdf file size 134kb) appear the most adapted (of the species investigated) to the conditions at these five landfills. Overall tree growth at Shaw has been the most impressive (See Photograph 5 below), with that at Grunty Fen the poorest.

Table 2.2 illustrates which sites and species are likely to have responded to the nitrogen applied as fertiliser in April 1999. At all five sites, ash grew more in 1999 than in any other year. This species has been noted in previous reports as the only one of the four better growing species (poplar, alder, cherry and ash) that had particularly poor foliar nutrient concentrations. Ash and whitebeam were the only species to be deficient in nitrogen at four of the five sites. The fertilisation of whitebeam and Corsican pine (which was deficient in phosphorus as well as nitrogen) may have helped growth at some, but not all, sites.

Figure 2.3: Growth at the five sites including 1999 increments (available to download below)

Table 2.2. Species achieving their maximum annual increment during 1999 (a indicates max. annual increment was achieved in 1999, x indicates it was not, = indicates it was equalled and a blank indicates the species is not present at the site)

Site	*ash*	*bee*	*pine*	*English oak*	*Hybrid larch*	*Italian alder*	*cyp*	*Silver maple*	*syc*	*pop*	*wtbm*	*Wild cherry*
Shaw Tip	a	a				x	a	a		x	a	a
Pimbo	a		=	x	x				x	x	x	x
Yanley	a		a	x		a			x	x	x	x
Beech Farm	a		x	a		a		a		a	=	a
Grunty Fen	a		a	a	x	a			a	a		a

Where : bee = beech, pine = Corsican pine; cyp = Leyland cypress, syc. = sycamore, pop = white poplar, wtbm = whitebeam.

Table 2.2 also shows that at Shaw Tip, Beech Farm and Grunty Fen, six of the eight species achieved maximum annual increments in 1999 suggesting a response to fertiliser application. This effect was most noticeable at Grunty Fen (Figure 2.3) where some of the few surviving trees appeared almost to have stopped growing prior to 1999. Trees at Yanley and Pimbo were relatively unaffected by fertiliser application during the 1999 growing season, except for the ash at both sites, and the alder at Yanley. It is possible that enhanced growth will occur during 2000 at these sites.

2.5 Nutrition

Foliar samples were collected from each site in August (deciduous species) and November (evergreens) 1998. The samples were analysed at the Forest Research Chemical Laboratories, in Farnham. The results were used to interpret the nutrient status of the trees with a view to fertilising the plots in 1999. The data used to determine fertiliser requirements are given in Table 2.3.

Table 2.3. Definitions of nutrient status based on foliar analysis (% oven dry weight)

species	*nitrogen*			*phosphorus*			*potassium*		
	Def.	Opt.	Max.	Def.	Opt.	Max.	Def.	Opt.	Max.
Ash	<2.0	>2.3		<0.19	>0.22		<0.7	>0.9	
Beech	<2.0	>2.3		<0.14	>0.16		<0.7	>0.9 /td>	
Oak	<2.0	>2.3		<0.14	>0.16		<0.7	>0.9	
Hybrid larch	<1.8	>2.5		<0.18	>0.25		<0.5	>0.8	
Italian alder	<2.5	>2.8		<0.16	>0.18		<0.7	>0.9	
Silver maple	<2.0	>2.3		<0.19	>0.22		<0.7	>0.9	
Sycamore	<2.0	>2.3		<0.17	>0.20		<0.7	>0.9	
White poplar	<2.0	>2.3	3	<0.17	>0.20		<0.7	>0.9	
Whitebeam	<2.0	>2.3		<0.17	>0.20		<0.7	>0.9	
Wild cherry	<2.0	>2.3		<0.17	>0.20		<0.7	>0.9	>1.5
Corsican pine	<1.2	>1.5		<0.12	>0.16		<0.3	>0.5	
Leyland cypress	<1.2	>2.3		<0.12	>0.16		<0.3	>0.5	

Def. = deficient, Opt. = optimum and Max = maximum yield

Limits given in shaded boxes are based on research; unless otherwise stated they are taken from Taylor, 1991. Non-highlighted limits are inferred from the data available.

Taylor (1991) gives 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 other species information from literature searches was often given as foliar concentrations required to produce maximum yield of either timber or fruit (Auchmoody and Smith, 1977; Ystaas et al., 1997; Callan and Westcott, 1996). This information was combined with that in Taylor (1991) to estimate deficient and optimal values for those species where no data are available.

Each species at the five sites has been defined as deficient, marginal or optimal for N, P and K. The results (Table 2.4) demonstrate that nutrient shortage was commonplace, and that nitrogen was the most deficient nutrient. 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. It is standard practice not to carry out foliar analysis on trees which have been in the field for less than three years as the results are frequently affected by nursery conditions prior to planting. The trees at Beech Farm and the alder at Yanley have just completed their third growing season and already show signs of deficiency.

Table 2.4. Foliar nutrient status at the landfill sites

Nitrogen

Species	Shaw Tip	Pimbo	Yanley	Beech Farm	Grunty Fen
Ash	# #	# #	#	# #	# #
Beech	# #				
Oak		#	# #	# #	# #
Hybrid larch		# #			
Italian alder			# #	no data	# #
Silver maple	# #			#	
Sycamore		# #	# #		no data
White poplar	#		#		#
Whitebeam	# #	# #	# #	# #	
Wild cherry	# #	#	#	#	#
Corsican pine		# #	#	#	# #
Leyland cypress	# #				

Phosphorus

Species	Shaw Tip	Pimbo	Yanley	Beech Farm	Grunty Fen
Ash					# #
Beech	#				
Oak			# #		# #
Hybrid larch					
Italian alder	#		#	no data	
Silver maple	#				
Sycamore					no data
White poplar					
Whitebeam					
Wild cherry					
Corsican pine		#	# #	#	# #
Leyland cypress					

Potassium

Species	Shaw Tip	Pimbo	Yanley	Beech Farm	Grunty Fen
Ash					
Beech	# #				
Oak		#			#
Hybrid larch					
Italian alder				no data	
Silver maple					
Sycamore		#			no data
White poplar					
Whitebeam					

Wild cherry					
Corsican pine				#	
Leyland cypress					

Key

species not present	
deficient	# #
marginal	#
optimal	

A species-by-species comparison of nutrient status has shown that poplar and cherry are best suited to the general lack of nitrogen. Poplar was not deficient in nitrogen at any of the sites and cherry was only deficient at Shaw Tip. These results agree with the growth data discussed above.

It may be expected that alder would not show signs of nitrogen deficiency. However, Table 2.4 implies that it is nitrogen deficient in comparison to alder on undisturbed land, probably because nitrogen fixation does not provide the tree with all of the nitrogen it needs (Hood, 1993). It is also possible that some alders were unnodulated and thus unable to fix atmospheric nitrogen.

Phosphorus deficiency was detected in Corsican pine at four of the five sites and lack of phosphorus may limit growth at these sites. With a probable nitrogen deficiency, this species may be difficult to establish on landfill (and other brownfield) sites without application of a compound fertiliser. The foliar data confirm that potassium supply is rarely a problem for woodland establishment on brownfield sites (Moffat and McNeill, 1994).

2.6. Discussion

The experimental plots, though comparatively young in age, have shown that trees of several species can be established on modern containment landfills restored to a modern specification. The results suggest that the species best suited to the conditions on the landfills include white poplar, Italian alder, whitebeam, wild cherry and, where moisture availability is not limiting, ash. However, other species may also achieve good growth under suitable conditions; examples include Leyland cypress and silver maple at Shaw Tip. Oak, too, grew well at all sites except Grunty Fen, and is clearly intolerant of droughty conditions.

It is a common forestry practice to apply fertilisers only *after* trees have established a root system on the new site. The positive growth response of some tree species to the fertiliser added in 1999 has demonstrated that such trees were able to take up this new source of nutrient. Nevertheless, Dobson and Moffat (1993) recommended that application of fertiliser *before* planting was justified on landfill substrates known to be deficient in one or more nutrients. Foliar analysis revealed the infertility of most soil materials used to restore landfill sites in this project, and it is possible that more rapid early growth might have been obtained if fertiliser had been applied at this stage.

Despite comparatively small nutrient demands, conifers can be remarkably difficult to establish on brownfield sites, especially on soils with a pH above 8. Both Corsican pine and Japanese larch were chosen because they are known to tolerate such soil conditions on similar sites in South Wales. However, tolerance does not imply good survival and growth rates. It is interesting that, in general, these species did not perform well in the survey of established woodland on landfills visited by Dobson and Moffat (1993).

Small pure species plots have the value that comparisons can be drawn between species and between sites where the same species are planted. However, there is a natural disadvantage because the scale of planting is small compared to normal woodland schemes, and the individual species offer no protection, or nursing effect, to one another. For example, alder is commonly interplanted with other species in woodlands established on brownfield sites, in the hope that it will help to supply nitrogen to the other trees. It is possible that larger growth rates would have been obtained in this way. Nonetheless, the rates of growth of the most successful species in all the experiments except Grunty Fen are comparable with those of trees planted on undisturbed land. Only those trees clearly suffering the effects of exposure, drought, alkaline soil conditions or browsing are growing more slowly.

2.7. Conclusions

The five tree species experiments are a valuable resource, both to inform on species tolerance and performance on landfill sites, and as a potential source of material on which to study root/landfill cap interactions in the future. The tree survival and growth results may be regarded tentatively as suggestive of future performance, but most species are in or just outside the establishment period, and changes to survival and comparative growth are still possible. More reliable information will be available as the monitoring plots mature. Selection of suitable tree species for a particular landfill should depend on likely growth under the local conditions, but may also be influenced by likely windthrow characteristics (Dobson and Moffat, 1993), as well as the broad needs for the woodland being planted.

Standard forestry practice (Dobson and Moffat, 1993, Chapter 6; Bending and Moffat, 1997, Chapter 4) is shown as suitable for establishing woodland on landfills. Nevertheless, fertiliser application is recommended before or soon after planting for sites where infertile soil materials are used in restoration.

Endnotes

1. Common and scientific names for the species referred to in this report are given in the Annex

Go to table of contents

3.0 Rooting characteristics at Waterford landfill site

3.1 Introduction

This part of the report describes, in detail, the results of a study into tree rooting habits at the restored landfill site at Waterford, Hertfordshire. Restoration at this site closely followed modern guidelines prior to planting in 1986. It therefore provided an opportunity to investigate root/cap interactions at a suitably restored landfill site on which the woodland is fully established.

3.2 Study site

The study site was located at the Robert Brett & Sons Ltd Waterford landfill site, Hertfordshire (grid ref: TL 307147). Here, the void left after sand and gravel extraction was filled with inert fill, and engineered to modern landfill standards, including the provision of a mineral cap about 1 m thick, passive landfill gas venting, and loose tipping of suitable soil-forming materials. The site has been restored to both agricultural and forestry after-uses.

To achieve a successful forestry plantation, ridges approximately 30 m wide and 1.5 m high were formed over the landfill cap, following guidance by Fourt (1980). These were constructed using a silty soil-forming material derived from silt-bed deposits, themselves a product of sand and gravel washing on site. Four tree species were planted: ash (*Fraxinus excelsior*), alder (*Alnus* spp.), sycamore (*Acer pseudoplatanus*)and Corsican pine (*Pinus nigra* var.*maritima*). Trees were planted in 1986, at two metre centres in rows of individual tree species running along the length of each ridge. The opportunity was taken by Forest Research at the time of tree planting to establish a replicated random block experiment which tested the effect of pre-plant fertiliser application on tree performance, and to set up the opportunity to study the effect of soil depth and ridge position on tree performance. The rooting characteristics of three of the species, sycamore, alder and Corsican pine, were examined in the present study.

The site forms a moderately steep hillside with average gradient of 7-8º, facing south and falling from 81 m to 61 m elevation. Average annual rainfall (1941-1971) for the area is 600-700 mm. The average accumulated maximum potential soil moisture deficit is 175-200 mm (Jarvis *et al*, 1984). The restored soil profile exhibited no evidence of periodic waterlogging and was probably freely draining, due to the low bulk density produced by loose tipping and the ability to transmit water laterally.

3.3 Methods

In May 1997, three transect lines were surveyed along the top of one ridge (approximately 1.3 m soil cover), its mid slope (approximately 1.0 m soil cover), and its basal position (approximately 0.5 m soil cover). Four trees, representing those growing most vigorously, were selected for each of the three species on each ridge position. This gave a total of 36 sample trees. Selection purposefully avoided suppressed trees.

The trench excavation procedure used to examine root systems was based on that described by Yeatman (1955) and Böhm (1979). Trenches were dug using a mini-digger in June 1997 (See Photograph 6 below). Care was taken to ensure that no trafficking over sampling positions took place, to prevent changes in the soil physical characteristics. Each trench was located within 15 cm of the tree stem.

Samples of the soil were taken at 25 cm thickness intervals to 1 m depth from four trenches at the crest of the ridge (maximum soil thickness), using Eijkelkamp soil coring rings driven into the face of the excavation pit using a wooden mallet. Bulk density was determined following methodology given by Hodgson (1997). The landfill clay cap was too compact and stony for this method to be used, so clods were taken and bulk density determined using the displacement method (BS 1377: Part 2: 1990). Stone material greater than 2 mm in diameter was subsequently removed by wet sieving. Stone density was then determined using the displacement method. The bulk density of the < 2 mm fraction of the cap was then calculated by recalculating the total cap bulk density. The particle size distribution of cap (n=9) and soil (n=20) was examined by dry sieve and pipette analyses, following the methodology in Avery and Bascomb (1982).

To examine the microstructure of the landfill cap and study how tree roots had penetrated into it, six undisturbed samples were removed 10-15 cm below the cap/soil interface at the base of the ridge. Four had obvious alder root intrusions. The samples were dried using acetone replacement in the laboratory, impregnated with a polyester resin, and made into thin sections using standard techniques (Lee and Kemp, 1992). Micromorphological analysis was performed on each thin section using a petrological microscope at *x* 10-100 magnification.

For each tree under study, trenches were excavated to below the cap/substrate interface. The front face of each trench was prepared for detailed examination of root distribution. A 5 cm layer of material was progressively removed from the entire surface area of the face using a trowel. The face was then delicately brushed to reveal all root ends. The mapping of roots was carried out immediately after exposure. The centre of the tree stem was taken as the vertical axis and the soil surface as the horizontal axis. All exposed roots were marked using red pegs (See Photograph 7 below). The co-ordinates of each root were then noted and the root diameter measured using callipers. The complete profile was mapped by repeating this procedure across the section, and removing each root marker, until all roots had been examined. Maps of root distribution were then generated using Surfer software (Golden Software, Inc.).

To quantify differences in tree growth across the plot, the height of all the trees in each experimental plot were measured using heighting rods. General yield class was estimated using top height/age curves for each species (Hamilton and Christie, 1973). Top height is defined as the mean height of the one hundred trees of largest diameter (at breast height) per hectare (Rollinson, 1991). Yield class is the maximum value of the quotient of total production/age, in m^3 ha^{-1} yr^{-1}, and is conventionally given in 2 m^3 ha^{-1} yr^{-1} intervals. These estimates should be treated cautiously because yield models assume normal patterns of growth which may not be applicable to trees growing on restored ground. In addition, trees of the age when sampled were only just old enough for predictions of yield to be made.

3.4 Results

Physical properties of the soil-forming material are shown in Table 3.1. Soil bulk density increased with depth as in a typical soil profile. Almost all values conformed to the standard set for restoration of disturbed land to a forestry after-use (<1.5 g cm^{-3} to 0.50 m depth; <1.7 g cm^{-3} from 0.50 to 1.00 m depth) (Moffat and McNeill, 1994). The cap had a mean moisture content of 12 % and a mean total dry bulk density of 1.99 g cm^{-3}. The minimum dry bulk density of 1.87 g cm^{-3} exceeded the minimum recommended for cap construction (Department of the Environment, 1986). The cap material particle size distribution was quite variable, but was dominantly clay loam with localised pockets of sandy silt loam. It also contained approximately 20% material > 2mm in diameter.

Table 3.1. Soil-forming material physical properties (n=20). ( ) standard deviation from mean.

Depth (cm)	*Average dry bulk density (g cm^{-3})*	*Moisture content (%)*
5	1.26 (0.18)	18 (3.4)
25	1.38 (0.13)	20 (3.9)
50	1.43 (0.10)	19 (6.6)
75	1.49 (0.12)	16 (6.6)
100	1.53 (0.09)	16 (3.8)

Table 3.2 summarises tree growth and rooting information from the study and Figure 3.1 is an example of root profiles obtained for one of the tree species. A significant correlation (r = 0.75, n = 37, $p<0.01$) was found between depth to the cap and the rooting depth of all species. This relationship was stronger for alder (r = 0.89, n = 13, $p<0.001$) than sycamore (r = 0.80, n = 11, $p<0.01$) or Corsican pine (r = 0.65, n = 13, $p<0.05$). Alder is a faster growing species than the others, and its greater exploitation of the soil would be expected. No significant relationship was found between the total number of roots and the thickness of soil-forming material.

Detailed examinations of rooting characteristics were carried out at the soil-cap interface. Alder had a higher root density at the cap interface than either of the other species. No roots >5 mm were observed at this depth under sycamore or Corsican pine. Larger roots (5 to 10 mm) were observed at the interface under alder. Roots were most prolific in pits dug at the base of the slope where soil materials were thinnest. No roots were observed at the soil-cap interface where soil was 1.3 m thick in summit positions. Where roots came into contact with the cap surface, most ran parallel to it (See Photograph 8, .pdf file size 112kb). Radial thickening of the roots was observed at the soil-cap interface, with an increase in radius of between 45 and 60 per cent when compared to the root radius above the soil/cap interface. However, a few (mainly alder) roots entered the cap in localised areas. The depth of rooting into the cap did not exceed 3 cm for sycamore and Corsican pine, though alder root penetration up to 30 cm deep was detected in one inspection pit.

Micromorphological analysis of the clay cap confirmed that the particle size distribution of the material was extremely variable. Distinct patches of material of individual particle size classes, ranging from clay to fine sand, were observed. Small fissures were common throughout the cap and may be partly due to desiccation between placement of the cap and its covering with soil-forming materials. Areas of clayey material had many fissures with a diameter of less than 50 µ m running through them. No roots were observed running along this type of fissure. Instead, they exploited much larger fissures up to 6 mm width which existed at both the boundaries between the coarse and fine material and within the areas of coarse material. Some fissures contained partially decomposed organic matter which may indicate the former presence of a root. Several live roots were observed in areas of coarser material which did not appear to be associated with natural fissuring.

Table 3.2. Effective soil rooting depth, total root number, depth to cap, tree height (1997), horizontal root density in the base of the trench, maximum depth of rooting into the cap and the diameter range of the roots observed penetrating into the cap.

Slope Position	*Species*	*Tree*	*Tree Height (cm)*	*Depth Of Soil Above Cap (cm)*	*Total No. Roots*	*Effective Soil Rooting Depth (cm)*	*Rooting Density (Horizontal) (No. m^{-2})*	*Max Rooting Depth Into Cap (cm)*	*Cap Root Diameter Range (mm)*
Base	Alder	1	709	61	24	56	14	6	1.0 - 3.0
		2	550	71	19	70	12	11	1.5 - 3.5
		3	570	57	22	57	14	30	1.5 - 5.0
		4	630	67	37	71	8	10	1.5 - 5.0
		5	486	71	33	76	24	12	1.5 - 4.5
	Corsican pine	1	395	58	11	56	0		
		2	440	70	16	70	8	1.5	1.0 - 1.5
		3	515	68	25	68	12	2	1.0 - 2.0
		4	456	55	11	45	8	1	0.5 - 1.0
	Sycamore	1	200	63	17	62	10	3	1.0 - 2.5
		2	348	62	18	62	0		
		3	260	65	17	64	0		
		4	290	64	16	63	0		
Middle	Alder	1	580	100	31	98	6	2	1.0 - 2.0
		2	610	100	43	87	4	2	1.5 - 2.0
		3	588	100	25	91	0		
		4	698	102	18	89	0		
	Corsican pine	1	453	105	19	90	0		
		2	504	100	21	95	4	1	0.5 - 1.0
		3	310	98	24	95	0		
		4	478	82	26	70< /td>	0		
	Sycamore	1	403	102	21	85	0		
		2	510	110	26	96	0		
		3	363	115	20	74	0		
		4	371	100	28	87	8	1	0.5 -1.0
Summit	Alder	1	565	118	20	112	0		
		2	710	133	22	96	0		
		3	740	114	17	110	0		

		4	627	119	39	90	0		
	Corsican pine	1	405	125	27	124	0		
		2	510	127	31	93	0		
		3	445	124	22	92	0		
		4	494	120	16	53	0		
		5	428	125	19	80	0		
	Sycamore	1	404	117	17	99	0		
		2	600	132	35	132	0		
		3	302	122	15	78	0		

Figure 3.1: Distribution of alder roots exposed in section (available to download below)

Tree survival averaged 83 %, ranging from 67 % for Corsican pine to 91 % for sycamore, reflecting the comparative difficulty in establishing bare rooted pine (Moffat and McNeill, 1994). Table 3.3 suggests that survival of pine was poorer on the ridge summits, probably because these positions are more exposed and suffer drier soil conditions than those lower down the slope (Moffat and Roberts, 1989). Significant positive correlations were obtained between mean tree height and soil cover thickness for all species (Table 3.3). The mean yield class (in m^3 ha^{-1} yr^{-1}) was 4 for sycamore, 8 for alder and 16 for Corsican pine.

Table 3.3. Correlation coefficients *(r)* **between soil thickness and tree survival and mean height.**

	Sycamore *(n=64)*	*Alder* *(n=64)*	*Corsican pine* *(n=48)*
Survival (1994)	ns	ns	-0.85 **
November 1990 height	ns	0.88 ***	ns
March 1992 height	0.67 *	0.87 ***	ns
April 1994 height	0.82 **	0.84 ***	ns
July 1997 height	0.83 **	0.91 ***	0.72 *

* P<0.05, ** P<0.01, *** P<0.001; ns = not significant.

3.5 Discussion

The mean bulk density of the cap is above the minimum recommended by Dobson and Moffat (1993) for preventing root penetration of landfill caps. The ability of the cap to divert roots was shown by both the change in direction and deformity of the majority of roots observed at the soil/cap interface. Apart from alder, those roots which entered the cap reached a maximum depth of 3 cm. These results suggest that the probability of tree roots of these species being able to penetrate through the whole cap is small. However, it does highlight the importance of forming a cap with a uniform bulk density sufficient to prevent root penetration. The variable particle size distribution and significant stone content of the cap were probable additional features which led to fissuring and root penetration. There is some doubt as to whether the cap would meet current standards for its construction (Department of the Environment, 1995).

The ability of some alder roots to penetrate the cap is of obvious concern. Several studies have shown that *Alnus* species have a comparatively high tolerance to anaerobic conditions (Westra, 1959; Diaconu *et al.*,1971). Coupled with micromorphological evidence for fissuring within the cap, this could explain why alder roots have penetrated up to 30 cm into it in certain places. However, the frequency of root penetration was closely associated with inadequate soil depth, and the results demonstrate that provision of an adequate thickness could prevent root penetration completely.

Micromorphological analysis confirmed the variability of the cap material and the presence of areas of coarse textured material which reduced the caps resistance to root intrusion. It is difficult to ascertain whether the sand fraction was present in the original cap or if it was washed into the cap from the overlying soil-forming material. However, it is more likely to be intrinsic to the cap material at this site.

The presence of fine fissures in the clay areas is to be expected at the moisture content observed. The absence of roots along these fissures gives some indication of the ability of the cap to withstand root intrusion. Larger fissures observed at the boundary between the coarse and fine textured areas have probably been formed through the swelling and shrinking action of the finer material. The inability of the coarse fraction to withstand such action (ie the low plasticity and shear strength of the coarse material) provided weak points, producing comparatively large fissures, which the alder roots exploited. The discrete patches of partially decomposed organic matter in some of these larger fissures may indicate the former presence of roots, which may have died back in times of anaerobic conditions.

Several roots were observed in areas of coarser material which do not appear to be associated with natural fissures. This could indicate that there was a fissure present but that it ran perpendicular to the plane of the thin section, thus obscuring its presence, or that the bulk density of the coarse fraction was insufficient to prevent direct root penetration.

Tree survival for all species was very high, and growth of alder and pine was good. Sycamore performed less well, probably because its greater nutrient demands were only partially met in the silty soil-forming material used for restoration. Growth of all species was strongly influenced by soil depth, probably through its control on available water (Moffat, 1995). Similar results on landfill were found by Moffat and Houston (1991) and add weight to the need to consider soil thickness as a means of ensuring adequate tree growth as well as for its protective role on capped sites.

3.6 Conclusions

This initial research has confirmed the view taken by Bending and Moffat (1997) that if landfill construction is of a sufficiently high standard, the risk to cap integrity is minimal. There is little doubt that a 1.0 metre thick clay cap compacted to a dry bulk density greater than 1.8 g cm^{-3} is capable of preventing root penetration. Roots will penetrate the cap only at weak points (i.e. areas with a dry bulk density less than 1.8 g cm-3) so it is important that consistent standards of compaction are achieved across the site. If the capping strategy recommended for tree planting is adhered to, it is unlikely that roots from tree species that are intolerant of soil anaerobism will penetrate into the cap. However, further research is required to identify species which, because of tolerance to anaerobism, may be unsuitable for planting over landfill unless a suitable thickness of soil is placed over the cap.

This study also confirms that trees can be grown satisfactorily on soil-forming materials, providing they meet minimum standards (Moffat and McNeill, 1994). It also supports previous recommendations that, without a suitable geotextile or bio-barrier, trees should not be planted on a soil cover less than 1.5 m thick.

Go to table of contents

4.0 General Conclusions

This phase of the landfill research project has been successful in maintaining the five tree species experiments, and performing valuable investigations on tree rooting habits at a landfill site restored to a modern specification. During this time, the tree plantations have become fully established, and have the potential for detailed study of tree root / landfill cap interaction in a few years time.

Inevitably, differences in performance between sites and tree species have manifested themselves during this research phase. Differences between sites can be explained largely by the physical quality of materials used as soil or soil-forming materials and the amount of precipitation received, itself determined by location in England (Table 2.1). For example, the rainfall at Grunty Fen is comparatively small. In addition, this site suffers from low water holding capacity consequent upon the materials being stripped and stored using earthscrapers, and a large shrink-swell behaviour in the clay soil-forming material. Thus, the poor survival and growth of trees at this site are reasonably understandable in spite of standard weed control during the establishment period.

Differences in behaviour between tree species may be due to a range of factors. These include variable quality of original planting stock, treatment of stock before planting, and the tolerance and adaptation of individual species to conditions at each site. Certainly, the comparatively poor performance of some species, for example Italian alder at Beech Farm is more easily explained by questionable stock quality than by constraints of the site. Nevertheless, the research has shown that across the five study sites, certain species, notably white poplar, Italian alder, wild cherry, whitebeam, oak and ash have prospered whilst others (e.g. larch and sycamore) have failed to do as well. It is reassuring that the research has shown that a number of native species can thrive on landfills, though it also demonstrates that some non-natives, such as Italian alder and silver maple, do well too. Thus, the study reinforces the adage that tree species must be chosen for their tolerance and suitability to the conditions offered at a site.

Unfortunately, guidance on species suitability based on the field trials, especially the identification of poplars and alders as types that do well on landfills, must be balanced against the results of the Waterford study where evidence of some root penetration of alder into the landfill cap was found. In addition, Bending and Moffat (1997) found experimentally that poplar roots were able to penetrate into compact clay materials. Of course, neither study showed that roots of these species disrupt the integrity of a clay cap, and no evidence of root penetration was found where an adequate (> 1.2 m) thickness of soil cover had been placed over the cap. It seems very unlikely that roots will penetrate through a cap to the extent that landfill gas can escape. Nevertheless, it seems sensible to repeat that 1.5 m of soil cover is necessary to ensure that tree roots do not pose a threat to cap integrity.

After six years, no evidence of hot spots, produced by landfill gas contamination of the root zone, has been detected at any of the five experimental sites. This is reassuring and suggests that the clay caps under the plots remain intact, and have not been disrupted by tree roots. Nevertheless, no excavations of tree roots have been performed in this research phase to examine their architecture. Such research seems very desirable at some point in the future the Waterford study was restricted to three species, and information on others is needed to improve guidance on species suitability. Using the Waterford study as a guide, we suggest that further studies of this kind should commence no earlier than about 2004 (2006 at Beech Farm).

Go to table of contents

References

Auchmoody, L.R. and Smith, H.C. (1977). Response of yellow-poplar and red oak to fertilization in West Virginia. *Soil Science Society of America Journal*, **41**, 4, 803-807.

Avery, B.W. and Bascomb, C.L. (1982). *Soil survey laboratory methods*. Soil survey Technical Monograph No. 6, Harpenden.

Bending, N.A.D. and Moffat, A.J. (1997). *Tree establishment on landfill sites. Research and updated guidance*. Forestry Commission, Edinburgh.

Böhm, W. (1979). *Methods of Studying Root Systems*. Springer-Verlag, Heidelberg.

British Standards Institution (1990). Soil for civil engineering purposes. *BS 1377: Part 2. Classification tests*. British Standards Institution, London.

Callan, N.W. and Westcott, M.P. (1996). Drip irrigation for application of potassium to tart cherry. *Journal of Plant Nutrition*, **19**, 163-172.

Department of the Environment (1986). *Landfilling wastes*. Waste Management Paper No. 26. HMSO, London.

Department of the Environment (1995). *Landfill design, construction and operational practice.* Waste Management Paper 26B. HMSO, London.

Diaconu, M. and Traci, C. (1971). The utilisation of raised gravel banks in river channels for forest plantations. *Stud. Cerc. Inst. Cerc. Silvice,* **28**, 135-150.

Dobson, M.C. and Moffat, A.J. (1993*). The potential for woodland establishment on landfill sites*. HMSO, London.

Fourt, D.F. (1980). Lowland production forestry - On Derelict Land. *Report on Forest Research 1980, Edinburgh*, HMSO, London, 24-25.

Hamilton, G.J. and Christie, J.M. (1973). Influence of spacing on crop characterisation and yield. *Forestry Commission Bulletin* **52**. HMSO, London.

Hodgson, J.M. (ed.) (1997). *Soil survey field handbook*. Soil Survey Technical Monograph No. 5, Silsoe.

Hood, R.C. (1993). *Nitrogen Fixation and Turnover in an Alnus glutinosa-open-cast-coal-spoil System.* Ph.D. thesis, Reading Univeristy.

Jarvis, M.G., Allen, R.H., Fordham, S.J., Hazelden, J., Moffat, A.J. and Sturdy, R.G. (1984). *Soils and their use in South East England*. Soil Survey Bulletin No. 15, Harpenden.

Lee, J.A. and Kemp, R.A. (1992). *Thin sections of unconsolidated sediments and soils: a recipe*. Centre for Environmental Analysis and Management Technical Report 2, Department of

Geography, Royal Holloway, University of London.

Moffat, A.J. (1995). Minimum soil depths for the establishment of woodland on disturbed ground. *Arboricultural Journal* **19**, 19-27.

Moffat, A.J. and Houston, T.J. (1991). Tree establishment and growth at Pitsea landfill site, Essex, UK. *Waste Management and Research* **9**, 35-46.

Moffat, A.J. and McNeill, J.D. (1994). Restoring disturbed land for forestry. *Forestry Commission Bulletin* 110. HMSO, London.

Moffat, A.J. and Roberts, C.J. (1989). The use of large scale ridge and furrow landforms in forestry reclamation of mineral workings. *Forestry* **62**, 233-248.

Rollinson, T.J.D. (1991). Management for timber production. In: *Forestry Practice*. (ed. B.G. Hibberd). Forestry Commission Handbook **6**. HMSO, London, 147-161.

Taylor, C.M.A. (1991). *Forest fertilisation in Britain*. Forestry Commission Bulletin 95. HMSO, London.

Westra, J.J. (1959). A preliminary study on the causes of growth disturbances in plantations on the N.E. polder. *Uitvoer. Versl. Bosbouwproefsta., Wageningen*, **4**, pp. 26.

Yeatman, C.W. (1955). Tree root development on upland heaths. *Forestry Commission Bulletin* 21. HMSO, London.

Ystaas, J., Froynesm O., Val, J., Montanes, L. and Monge, E. (1997). Young sweet cherry trees respond favourably to phosphorus fertilization. *Acta-Horticulturae*, **448**, 383-387.

Go to table of contents

Annex

Common and scientific names for the tree species referred to

Alder, Common	*Alnus glutinosa*
Alder, Italian	*Alnus cordata*
Ash	*Fraxinus excelsior*
Beech	*Fagus sylvatica*
Cherry	*Prunus avium*
Cypress, Leyland	**X** *Cupressocyparis leylandii*
Larch, Hybrid	*Larix eurolepis*
Maple, Silver	*Acer saccharinum*
Oak, English	*Quercus robur*
Pine, Corsican	*Pinus nigra* **var.** *maritima*
Poplar, White	*Populus alba*
Sycamore	*Acer pseudoplatanus*
Whitebeam	*Sorbus aria*
Whitebeam, Swedish	*Sorbus intermedia*