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Woodland Establishment on Landfill Sites

Ten Years of Research

Forest Research

May 2008
Department for Communities and Local Government

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Executive Summary

Field experimentation on modern landfills

In 1993-4, experimental tree species plots were set up on five modern clay capped landfill sites across England, following newly proposed standards for tree establishment. Initial data collection indicated that useful insights into tree species most tolerant of site conditions on landfills could be gained. This report presents an overview for the tree species experiments over the last 10 years, including data collected in the most recent project contract period (1999 to 2003).

The tree performance data over the ten years of the research (1993 to 2003) indicated the following:

1. Tree survival rates for most species remain at levels between 50 and 85% of those originally planted in 1993 (i.e. not including consideration of replacement trees). Some species have survived exceptionally well considering the hostile landfill site conditions, including white poplar, whitebeam and ash.
2. Most species in 2003 had reached heights of between 2 and 6 metres, except at Grunty Fen where heights were between 1 and 4 metres. Trees appear to have reached a height at most sites where they are less susceptible to site influences of grazing or weed competition.
3. The trees have shown a reasonably steady increase in height over the 10 years, with growth rates differing between species and sites. Growth rates have been relatively steady since 1999, but appear to be slightly slower than in 1997 and 1998.
4. The fastest growing species remain poplar, alder, cherry, whitebeam and ash. However, actual height is a reflection of both species growth habit and overall performance so caution is required in comparing heights between species. Indicative Yield Class calculations suggest that most woodland tree species are performing reasonably against expectations.
5. Drought appears to be the key factor limiting tree growth, particularly at the Grunty Fen site. A very dry summer in 1995 also affected tree survival and growth rates at all sites, but most notably at Beech Farm where all experimental plots were replanted in early 1996 due to heavy tree losses.
6. All sites show signs of nitrogen deficiency, with very few deficiencies in phosphorus or potassium being encountered. Further nitrogen fertiliser applications may be required before canopy closure is reached for some species.
7. There are slight indications that the tallest trees, those exceeding 6 to 7 metres in height (notably white poplar), show signs of encountering limitations to growth. This may be a result of conditions within the soil cover or due to the presence of the landfill cap but this has not been confirmed by any further experimental investigation.

Study of tree rooting at Waterford landfill site

The trees planted on the five landfill sites are still relatively young and the full implications of tree root / cap interactions were not expected to be realised until the trees were at least ten years in age. Experimental work was therefore conducted to examine the extent of tree rooting in the soil cover and cap at the Waterford Landfill site, Hertfordshire. Woodland blocks comprising four tree species (alder,

ash, sycamore and Corsican pine) had been established at this site in 1986 in a former experiment designed to investigate tree performance response to fertiliser applied at the time of planting. Trees were planted on large ridges approximately 30 m wide constructed in silty soil-forming material over a compacted landfill cap. The ridge and furrow landform was that recommended for woodland establishment on sites reclaimed after mineral extraction or landfilling (Wilson, 1985). The site thus offered a valuable opportunity to study the impact of tree rooting on the integrity of the landfill cap and to evaluate the effect of soil depth and ridge position on tree performance. Investigations were initially conducted by Forest Research in May 1997 (Kennedy *et al*., 2000; Hutchings *et al*., 2001), when the trees were 11 years old, to examine tree rooting distribution and depth and study soil and cap physical conditions. The study was repeated in 2002 when the trees were aged 16 years.

The results of the 1997 study showed that:

1. the incidence of roots reaching the soil / cap interface was greatest where the soil cover was thin (less than 0.6 metres);
2. no roots were observed at the soil / cap interface in 1997 where the soil cover was at its maximum of 1.3 m thick;
3. alder, the fastest growing species, had a higher root density at the soil / cap interface than the other species and produced the maximum depth of root penetration into the cap of 0.3 m at this time.

The 2002 rooting study revealed the following results:

1. Average tree height had increased since 1997. Alder remained the tallest species, followed closely by ash. The growth rate of alder appeared to have slowed and the relative height difference between the species had closed since 1997.
2. The average root count per tree (irrespective of species) rose from 22.9 in 1997 to 128.0 in 2002.
3. The tree rooting systems are still developing and the full impact of tree rooting on the landfill cap has not yet been reached. The 1997 data indicated that very few limitations to root growth were being encountered as a result of soil cover material thickness or depth to cap for trees of age 10 years. By 2002, however, the count of roots approaching the soil / cap interface had multiplied by up to 15 times the 1997 value.
4. The average proportion of the total root count approaching the cap remained low, at 4%, in 2002.
5. There was a strong and significant relationship between the thickness of the soil cover and the number of roots per tree entering the cap. Where soil thickness was 65 cm or less, an average of 9.3% roots entered the cap, compared to an average of 3.2% for all those roots studied irrespective of depth. Less than 1% of roots were predicted to enter the cap where the soil cover depth (or depth to the cap) is greater than 1.25 metres.
6. Approximately 50% of the total root count approaching the soil / cap interface succeeded in penetrating into the cap, although this represented less than 3% of all roots counted.
7. The mean depth of root incursion into the cap was 0.3 metres, although one root reached the maximum depth of incursion of 98 cm into the cap.

8. Alder and sycamore produced the greatest number of roots approaching within 3 cm of the soil / cap interface, the greatest number of roots penetrating into the cap and the greatest rooting depths within the cap.
9. Micromorphological analysis and evaluation of cap bulk density indicated that the landfill cap presented a relatively porous environment with a high degree of heterogeneity in porosity and particle size.
10. Cap densities where roots were observed typically ranged from approximately 1.5 to 1.6 g cm^{-3} and were not typical of a modern compact and non-porous clay cap environment. Various features of the cap, including crack development and high sand content, appeared to allow root incursion.
11. Portions of the cap with high clay content and fine pore size appeared to resist root incursion successfully.

In support of the findings of the 1997 investigation (Kennedy *et al*., 2000; Hutchings *et al*., 2001), the results of the root study show:

1. At least 1 metre of soil cover is required to enable sustainable growth to be maintained for trees of age up to 10 years. In droughty areas or in soils with low moisture-holding capacity, a greater soil cover depth is likely to be required to support the moisture demands of mature trees.
2. The provision of 1.5 m of soil or soil-forming material overlying a mineral cap will ensure that trees can be established on landfills without posing a significant threat to cap integrity up to their 16^{th} year.
3. The micromorphological study suggests that the Waterford landfill cap composition appears not to be of sufficiently high standard to resist root penetration. To put the results into perspective, in the deepest soil covers the total proportion of roots entering into the cap was only about 2%.
4. The cap did not meet the modern standard of 1.8 g cm^{-3} density, which is recommended by Waste Management Paper No. 26 (Department of the Environment, 1986). The evidence collected to date at Waterford has shown no evidence to contradict the validity of this standard, since denser fabric within the cap appeared to resist root incursion. This also poses a question, however, about the number of landfill sites that have attained a uniform cap bulk density to this standard in reality.
5. The results suggest that it is still a little early to ascertain the full impact of tree rooting on cap integrity or the interaction between conditions within the landfill cap and tree rooting.

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Preface

This publication is an update on experimental work first begun in 1993, following publication of the 1993 report *The Potential for Woodland Establishment on Landfill Sites.* The research was initially intended to investigate the establishment and performance of woodland on landfill sites, supplemented by studies into soil moisture characteristics under grass and woodland, and laboratory studies of tree root exploration into simulated landfill caps. The first three years of results (1993 to 1995) were presented in the 1997 report *Tree Establishment on Landfill Sites: Research and Updated Guidance.* A subsequent three year contract (1996 to 1998) was issued to continue the long-term tree performance monitoring and to investigate tree root exploration into a real landfill cap at the Waterford site, in Hertfordshire. The results were presented in an end-of-contract report in 1998 entitled *Woodland Establishment on Landfill Sites – Site monitoring*. A further four year contract was issued between 1999 and 2003 for the same purposes. This report represents the end-of-contract report for the 1999 to 2003 contract but presents an overview of the full ten years of field experimental evaluation commissioned by the Office of the Deputy Prime Minister.

The views expressed in this report are those of the contractor and do not necessarily represent those of the Office of the Deputy Prime Minister or any member of the Steering Committee.

The Department of the Environment (DoE) was renamed the Department of the Environment, Transport and the Regions (DETR) on 16 June 1997. This Department was subdivided into the Department of the Environment, now the Department for the Environment, Food and Rural Affairs (Defra), and the Department for Transport, Local Government and the Regions (DTLR). The DTLR's responsibilities were principally transferred to the Office of the Deputy Prime Minister on 29 May 2002. All work conducted and any references in the text to commissions to the former DoE, DETR or DTLR are now under the aegis of the Office of the Deputy Prime Minister.

Acknowledgements

This study was commissioned and funded by the Minerals and Waste Planning Division of the Office of the Deputy Prime Minister. A financial contribution was also made by the Forestry Commission's Sustainable Forestry Group. We are particularly grateful to the Department's Nominated Officer Roger Orpin, (ODPM Minerals and Waste Planning Division), and to the Steering Committee for their helpful guidance: Dr Tom Simpson (Chair and formerly the nominated project officer, ODPM Minerals and Waste Planning Division), Mr Brian Freeland (Secretary, ODPM Minerals and Waste Planning Division), Peter Annett (Rural Development Division, ODPM), Peter Gawn (Land and Mineral Resource Consultants Limited), Roy Romans (Principal Minerals Planning Officer, Bedfordshire County Council), Elizabeth Simmons (Robert Long Consultancy), Chris Anniss (Swindon Borough Council), Stephen Redwood (RMC Technical Services Ltd), Jenny Thomas (Environment Agency), Ian Lanyon FRICS (FAAN Regional Estate Manager - Southern Aggregate Industries UK Ltd), Gene Wilson (M J Carter Associates), Alex Finn (RMC).

We wish to thank the landowners and landfill operators who allowed the establishment of woodland trials and who continue to support the experimental study of tree growth on their land. We wish particularly to thank Brett Aggregates Ltd for their permission and their continued support of the rooting into landfill caps experiment. We are grateful to Professor R. Kemp and Mr A. Palmer of Royal Holloway and Bedford New College for preparation of thin sections and Dr S. Mooney for provision of contract and analytical services for micromorphological analysis. We also wish to acknowledge the work by colleagues at Forest Research especially Andy Peace for conducting the statistical analysis, Lesley Halsall for providing the regional Yield Class data, and Nick Tucker, Ralph Nickerson, Brian Hanwell, Dave West, Dave Rogers, Kate Harris, Bob Bellis, Tony Hutchings, Danielle Sinnett and Oliver Rendle for help in assessing the experiments.

1. INTRODUCTION

1.1 BACKGROUND

The establishment of some form of vegetation is a vital part of the restoration strategy for most landfill sites (Department of the Environment, 1996). The choice of vegetation is especially important as it affects the appearance of the site and the way it fits into the wider landscape. Early guidance issued by the Department of the Environment in 1986 actively discouraged tree planting on capped landfill sites.

Principal concerns about woodland planting on landfill sites have included the following perceptions:

1. Tree roots could penetrate through an engineered landfill cap, allowing water ingress or escape of landfill gas.
2. Tree rooting systems might tend to be shallow rooting due to the presence of dense soil layers or cap material and woodland establishment might disrupt or compromise landfill pollution control measures if the trees were to blow over.
3. Tree survival and performance might be poor or adversely affected by landfill site conditions.

The 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:

1. the likely patterns of tree root growth on landfill sites;
2. the ability of tree roots to penetrate a landfill cap;
3. the likelihood of tree risk from windthrow;
4. the ability of trees to grow on the comparatively harsh environment of a landfill site.

The findings of the 1993 study suggested that it was possible to establish trees on modern containment landfills provided:

1. the sites were engineered to a standard suitable for effective pollution control;
2. the landfill cap was well compacted (bulk density >1.8 g cm^{-3});
3. there was sufficient thickness of soil to prevent tree root penetration of the cap beneath.

The Department of the Environment acknowledged that restrictions on tree planting on landfill sites were based on little field experience or scientific evidence. However, the findings of the desk studies were drawn from research not directly involving the landfill environment, since pre-1986 guidance had effectively prevented tree planting on recent landfill sites, from which direct observations could have been made.

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). The then Department of the Environment and its successors, now the Office of the Deputy Prime Minister, have therefore funded a programme of study since 1993 with two main aims:

1. To establish and monitor field experimental plots on landfills which had been constructed close to the specifications identified by Dobson and Moffat (1993).
2. To evaluate the potential opportunities for and limitations of tree planting on landfill sites.

The aim of the research programme is to provide information about the suitability of woodland establishment on landfill sites, the longer-term performance of trees and the impact of tree rooting on landfill cap integrity.

Research has been conducted on several different experiments and over three discrete phases. Bending and Moffat (1997) produced the report "*Tree Establishment on Landfill Sites: Research and Updated Guidance*" which reported upon:

1. the first three years following establishment of woodland performance monitoring plots on five landfill sites (1993-1995);
2. measurements of soil moisture beneath established woodland and grass;
3. tree root exploration in simulated landfill caps;
4. laboratory investigations on the ability of tree roots to penetrate compact substrates.

Kennedy, Hutchings and Moffat (2000) produced a report on *"Woodland Establishment on Landfill Sites – Site Monitoring"* which examined the results of the second research phase including:

1. a continuation of woodland performance monitoring on five landfill sites (1996-1998);
2. a study in 1997 of rooting habits of three tree species of age 11 years on a mineral capped containment landfill at Waterford.

The most recent research (Foot and Moffat, 2002, 2003) examined the results of the third research phase including:

1. the continuation of woodland performance monitoring on five landfill sites (1999-2003);
2. a re-examination in 2002 of rooting habits of three tree species of age 16 years on the mineral capped containment landfill at Waterford.

The research programme to-date has thus examined the impact of tree roots, growing under controlled conditions in the field and the laboratory, on different cap materials. Studies of the establishment and early performance of a range of tree species growing on different soil cover materials over landfill caps were initiated in 1993 and are ongoing. It was recognised that a considerable period of time would elapse before these trees would reach a size to enable the full impact of rooting on landfill caps to be evaluated. Thus, investigations were instigated in 1997 and 2002 to examine interactions between rooting and the landfill cap for well-established trees of age 10 and 16 years at the Waterford landfill site in Hertfordshire.

This report presents the results of the field-based experiments into tree performance monitoring on the five landfill sites between 1993 and 2003 and the investigations of rooting into the landfill cap at the Waterford site in 1997 and 2002.

1.2 OBJECTIVES OF THE RESEARCH

The research had three main objectives:

1. To examine the establishment success of woodland on modern engineered containment landfill sites with soil cover and cap systems which conformed to the recommendations given in *The Potential for Woodland Establishment on Landfill Sites*.
2. To monitor woodland growth performance, species selection and site management requirements on landfill sites.
3. To examine the impact of tree rooting on landfill cap integrity in the short and long-term including the ability of tree roots to explore and penetrate the cap and the long-term impact of rooting and moisture extraction on cap integrity.

Long-term woodland performance monitoring plots were established on five modern landfill sites in order to fulfil objectives 1 and 2. These were planted in 1993 and tree survival, growth and management inputs were recorded on an annual basis between 1994 and 1999 and every two years thereafter to 2003. The results of tree establishment and performance studies (points 1 and 2) are presented here in Chapter 2.

A number of studies were conducted in order to meet objective 3:

- Laboratory investigations to assess the ability of tree roots to penetrate compact substrates, including:
  - tree root growth in clays compacted to different levels of bulk density;
  - interactions between bulk density and penetrability as a means of predicting rootability of clays.
- Two-year nursery studies of tree root exploration in landfill capping systems, using simulated clay cap materials and barrier systems or strategies commonly used in containment landfills that are not only designed to control rainfall infiltration but also to prevent root penetration.
- Field studies of soil moisture demands under mature woodland cover compared to an established grass cover on a natural heavy clay soil, to predict the physical behaviour of a clay underlying a mature woodland cover and hence to establish the potential for shrinkage or cracking of buried clay caps at landfill sites.
- Field-scale examination of the rooting distribution of growing trees (age 11 and 16 years) planted as part of the restoration landscape on a modern capped landfill site at Waterford in Hertfordshire.
- A micromorphological investigation into the penetration of tree roots into the Waterford landfill cap.

The laboratory and nursery studies and the soil moisture field studies were commenced in September 1993 and completed in February 1996 and were reported in the 1997 report "*Tree Establishment on*

Landfill Sites: Research and Updated Guidance", so are not repeated here. The Waterford studies (points 4 and 5) were conducted in 1997 and repeated in 2002 and the results are presented here in Chapter 3.

This report summarises, in some detail, the individual projects listed above, and discusses their findings in relation to the case for tree planting on containment landfill sites. It updates findings presented in the 1997 report *"Tree Establishment on Landfill Sites: Research and Updated Guidance"*. It is not intended to replace the report *The Potential for Woodland Establishment on Landfill Sites,* but rather to update certain sections.

1.3 STRUCTURE OF THE REPORT

This report aims to summarise and re-evaluate the findings of the research studies to-date and to use the results to update guidance and best practice. Chapters 2 and 3 summarise the overview and main findings of the most recent experimental work, namely the long term tree performance monitoring and the rooting into landfill studies conducted at Waterford. A discussion of the findings of the research programme to date and recommendations for improved landfill and forestry practice are presented in Chapter 4. Chapter 5 provides a short concluding section.

2. REVIEW OF TREE PERFORMANCE ON LANDFILL

2.1 INTRODUCTION

This chapter summarises the main findings of the tree performance trials conducted over ten years on five modern containment landfill sites. This field-based research has formed the main component of the landfill project.

2.2 OBJECTIVES

The tree performance monitoring experiment had three objectives:

1. To examine the survival characteristics and growth performance of a range of tree species under a range of different soil and climatic conditions on capped landfill sites.
2. To identify any key limitations to establishment success or growth.
3. To give recommendations for landfill site design, reinstatement and ground preparation, species selection, best practice planting and site maintenance procedures.

2.3 THE STUDY SITES

A screening process was used to evaluate the characteristics of a large number of landfill sites identified by the Environmental Services Association (ESA) and Waste Licensing Authorities. To select appropriate sites for the study, essential criteria were:

1. the presence of an engineered clay cap;
2. an uncompacted soil cover with a minimum thickness of 1.0 metre (as recommended by Dobson and Moffat, 1993);
3. at least one site to be located in a region receiving high annual rainfall;
4. a range of soil types and climatic conditions to be represented;
5. at least one site to comprise alkaline soils.

Five sites were selected which reflect a range of site conditions in terms of fill composition, climate and soil type. The sites chosen were located at Bristol (Yanley), Swindon (Shaw Tip), Skelmersdale (Pimbo), Hatfield (Beech Farm) and Ely (Grunty Fen). Site characteristics are summarised in Table 1 and the locations of the sites are shown in Figure 1. Perhaps unusually, all the sites had soil or soil-forming materials with neutral or alkaline soil reaction, which favoured choice of broadleaved tree species.

2.4 METHODS

Reclamation and woodland establishment practice at the sites followed, as closely as possible, the recommendations in *The Potential for Woodland Establishment on Landfill Sites*. Eight tree species were planted (total 1152 trees) at each site in a fully replicated experimental design with four blocks.

Tree species were chosen from a list recommended for community woodland projects, with consideration given to tolerance to soil pH, texture and risk of drought in the final selection. The final selection for each site was taken from the following list: ash, beech, Corsican pine, English oak, hybrid larch, Italian alder, Japanese larch, Leyland cypress, Norway maple, silver maple, sycamore, whitebeam, white poplar, wild cherry[1]. Table 2 indicates the species planted at each site. At Yanley, Beech Farm, Pimbo and Grunty Fen a selection of broadly similar species was made. At Shaw Tip, four particularly alkali-tolerant species were selected: Italian alder, beech, Leyland cypress and silver maple.

Table 1: Details of the five experimental sites

	BEECH FARM	GRUNTY FEN	PIMBO	SHAW TIP	YANLEY
Owner of site	RMC Aggregates (Greater London) Ltd	East Waste Ltd	Lancashire County Council	Thames-down Borough Council	Terry Adams Ltd
National grid ref.	TL 200100	TL 497798	SD 512040	SU 122858	ST 556698
Altitude (m. O.D.)	80	13	105	100	20
Annual rainfall (mm)	675	550	900	700	900
Soil and soil-forming materials	Sandy loam topsoil and subsoil	300 mm clay topsoil over clay subsoil	Imported, various	Coral Rag limestone	100 mm topsoil over Keuper Marl
Ground preparation	'Complete' cultivation to 1.0 m using excavator	'Complete' cultivation to 1.0 m using excavator	Loose tipping	Loose tipping	'Complete' cultivation to 1.0 m using excavator
Soil thickness (m)	1	1	1.5	1.5	1.5
Soil pH	6.9-7.2	7.3-8.1	8.0-8.7	8.3	8.0-8.3
Planting Year	1993/96	1994	1994	1994	1994

Figure 1: Long-term tree performance monitoring sites

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

Table 2: Tree species at the five experimental sites (✓ = planted)

Species	Beech Farm	Grunty Fen	Pimbo	Shaw Tip	Yanley
ash	✓	✓	✓	✓	✓
beech				✓	
Corsican pine	✓	✓	✓		✓
English oak	✓	✓	✓		✓
hybrid larch			✓		
Italian alder	✓	✓ (post Jan 1996)		✓	✓ (post Jan 1996)
Japanese larch		✓ (to Dec 1995)			✓ (to Dec 1995)
Leyland cypress				✓	
Norway maple	✓ (to Jan 1996)	✓ (to Dec 1995)			
silver maple				✓	
sycamore	✓ (from Jan 1996)	✓ (post Jan 1996)	✓		✓
whitebeam	✓	✓	✓	✓	✓
white poplar	✓	✓	✓	✓	✓
wild cherry	✓	✓	✓	✓	✓
Planted/replanted	1993/1996	1994	1994	1994	1994

Bare rooted transplants were used, except poplar which were planted as cuttings, and pine and cypress which were cell-grown. Trees were planted at 1.5 m spacing following standard practice for brownfield and urban sites (Moffat and McNeill, 1994, Hodge, 1995). The Beech Farm site was planted in March 1993 and the four other sites between December 1993 and March 1994. 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 therefore totally cultivated to 1 m depth in autumn 1995 prior to complete replanting of the experimental plots in January 1996. Trees were protected from animal browsing using standard forestry fencing. Weed growth was controlled using contact and residual herbicides for the first three years of the Project and thereafter by selective mechanical weeding once or twice per year if required. Weed control ceased when trees had grown to sufficient height to be relatively unaffected by weed competition, at Beech Farm in 2001 and at the other sites in 1999. Nitrogen fertiliser was applied to all sites in April 1999 and April 2002 following foliar analysis which indicated that many of the trees suffered from nitrogen deficiency.

Tree height was measured at planting and the condition and survival of trees assessed in July each year, with visits in September to determine precise failure numbers. Tree heights and growth increment were measured annually in the dormant season (November to March) between 1994 and 1999 and then in 2001 and 2003. Throughout the duration of the experiment, all failed trees were replaced with new plants or “beat-ups” in the winter following each height assessment.

2.5 RESULTS AND DISCUSSION

This report presents an overview of tree performance data collected over the ten year duration of the experiment from 1993 to the most recent measurements between 2000 and 2003. Data have been collated and re-assessed for this report, to eliminate small discrepancies between data handling methods in previous years by different authors[2].

2.5.1 Survival

Figure 2 presents the tree survival results for the experiment after ten years and Figure 3 illustrates the change in survival rate since planting. The results are based on the original stock (i.e. trees planted in the first year, results for beat-ups are not shown[3]).

Considering the range of species, tree survival performance has been best at Shaw Tip and worst at Grunty Fen. Most sites showed an initial decline in the total number of trees of each species, but this has tended to stabilise with time. In general, survival has been 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 species on the experimental plots.

The early decline in stand numbers, for example at Shaw Tip, is likely to reflect the quality of planting stock and maintenance rather than the effects of the landfill environment, although the site conditions at, or shortly following, the time of planting may have played a role in early survival. No site has exhibited an indication of dieback due to landfill gas generation within the soil cover but extreme over-winter site wetness or prolonged spring drought following planting can affect survival numbers. Differences in survival rate between species over the longer term may be explained by the general tolerance of the different varieties to specific site conditions. At Shaw Tip, the survival rate stabilised within two years of planting, while at Pimbo some species showed a continued decline in numbers, which may be related to their poor suitability to the exposed condition of the site. 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 (refer to Figure 6 and Figure 7 for indicative mean annual and mean summer rainfall conditions, respectively).

The results from the landfill experiments can be compared with published estimates of tree survival in similar situations. Bradshaw *et al*. (1995) reported that in urban settings, approximately 10% of newly planted trees die in their first year, but that up to 50% death often occurs in a five or six year period. In a survey in 2000 of woodlands established on brownfield land in England, Moffat and Laing (2003) found that 63% of sites planted at 2 m spacing mainly between 1994 and 1998 had tree densities between 64 to 80% of original density at the time of survey. Taken together, they suggest comparable results with the landfill experiments, though some species at some sites are clearly unsuited to the prevailing conditions.

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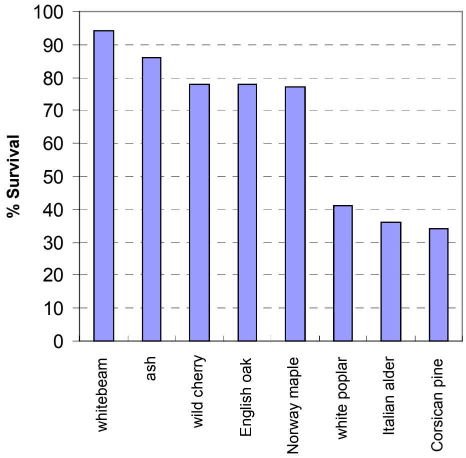
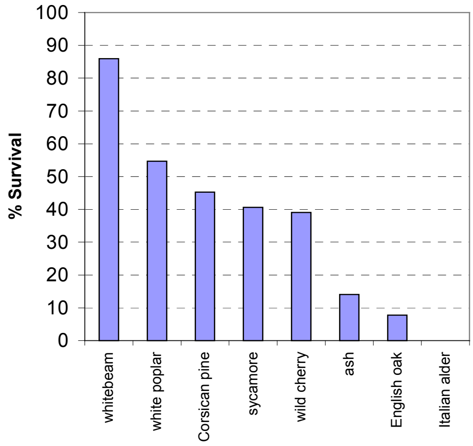
[2] For example, statistics for "beat-ups" were included in the Kennedy *et al*. (2000) report but not in the Bending and Moffat (1997) report.

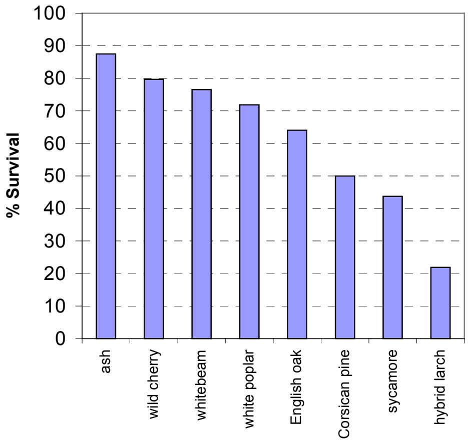
[3] except for replanting of whole-plots which are indicated as notes appended to each graph. The whole experimental area at Beech Farm was replanted following very severe losses incurred in 1995. Results for the failed species and beat-ups are not shown.



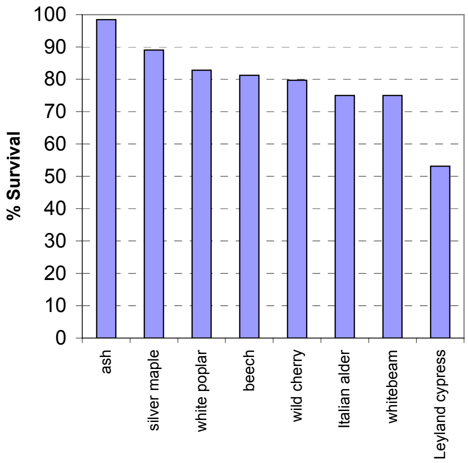
a) Beech Farm (replanted 1996)



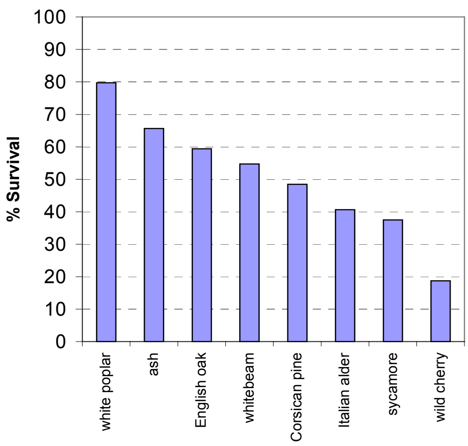
b) Grunty Fen



c) Pimbo

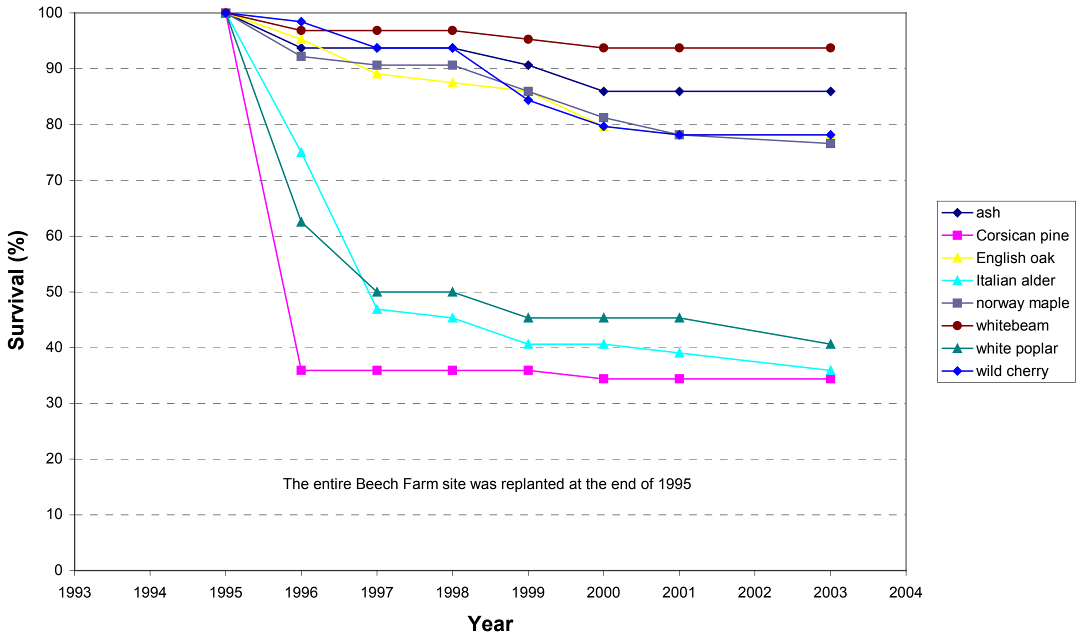


d) Shaw Tip

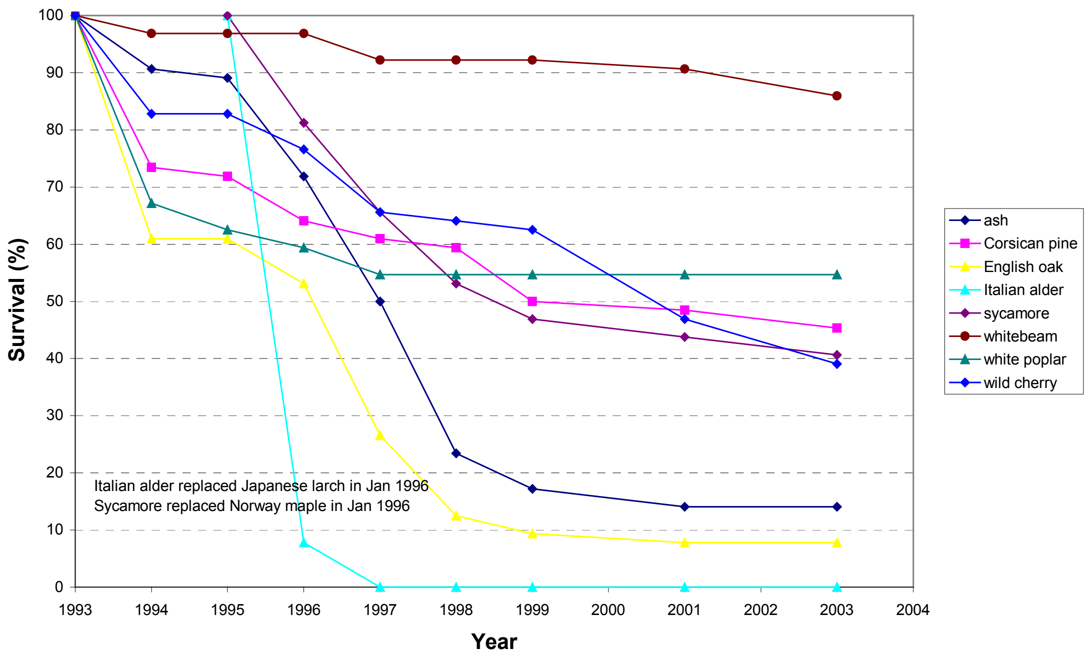


e) Yanley

Figure 2: Survival at the five landfill sites after ten years

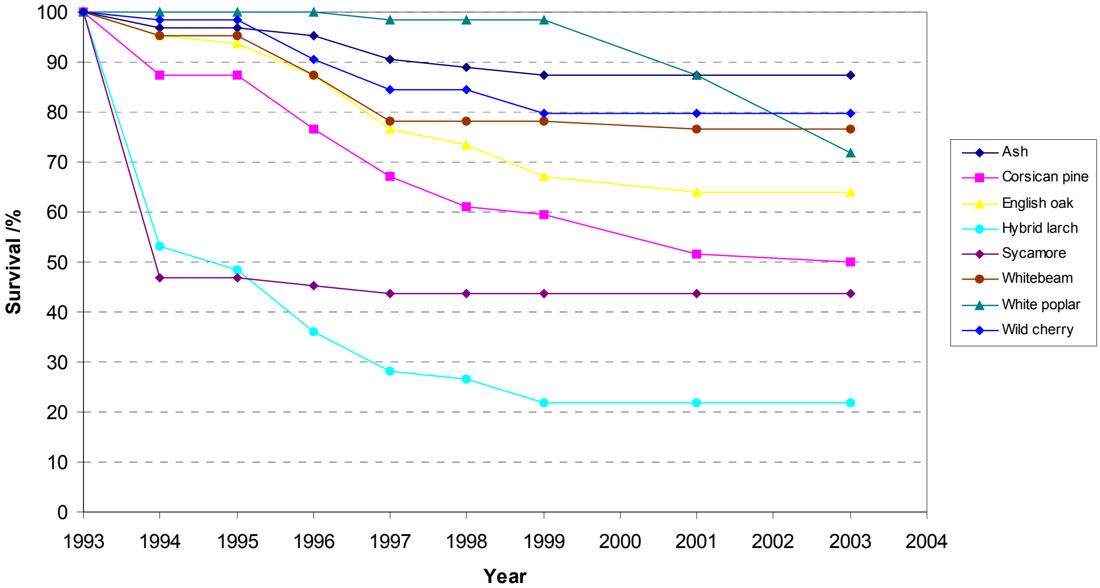


(a) Beech Farm (replanted January 1996)

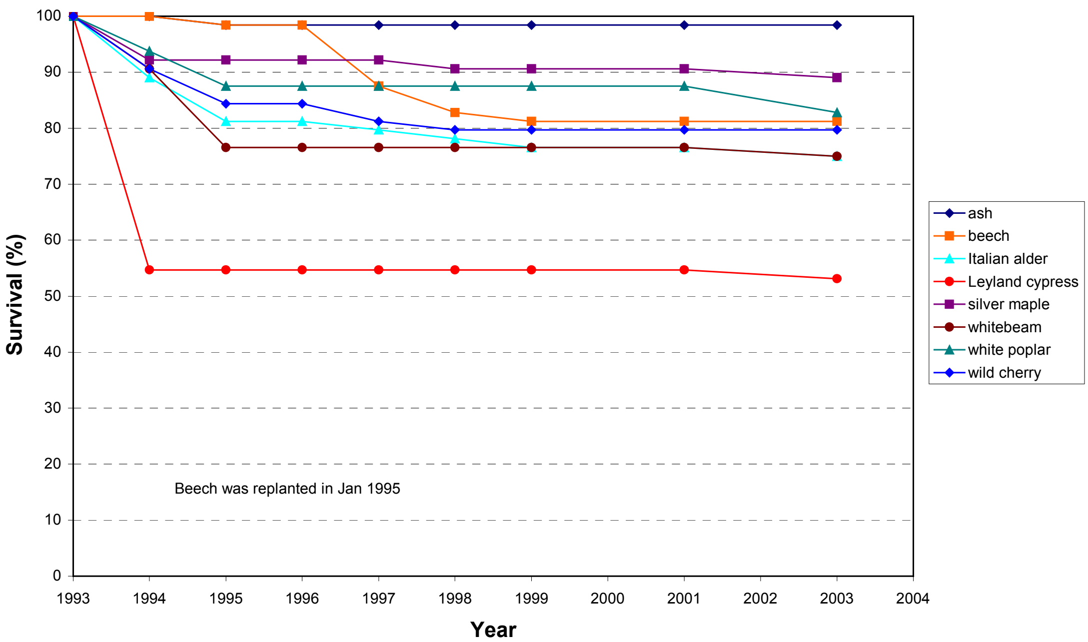


(b) Grunty Fen

Figure 3: Changes in survival rate since planting

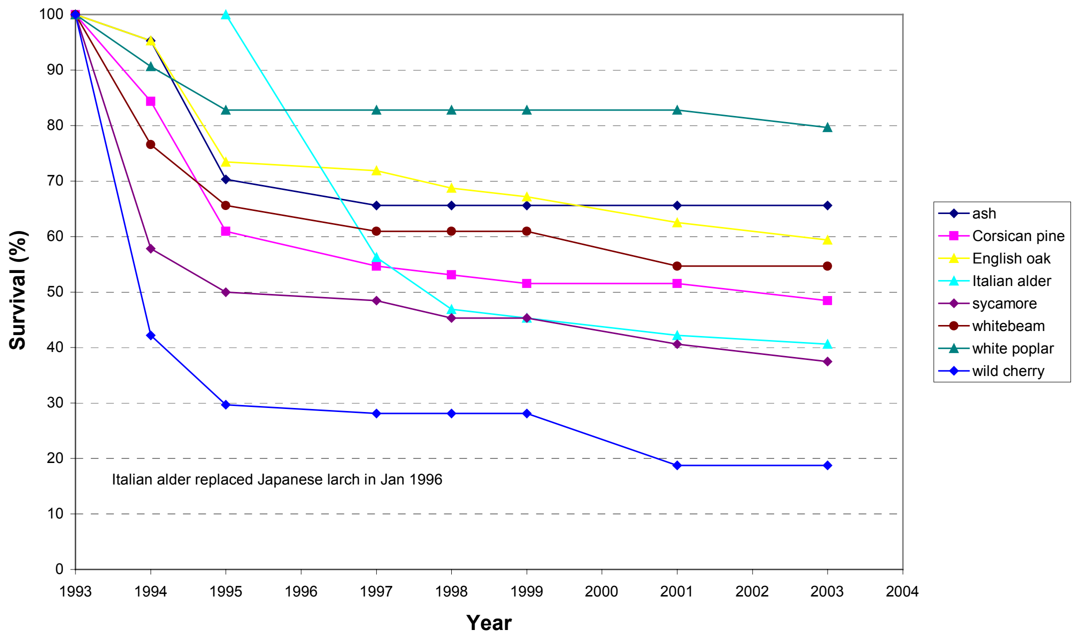


(c) Pimbo



(d) Shaw Tip

Figure 3 cont'd: Changes in survival rate since planting



(e) Yanley

Figure 3 cont'd.: Changes in survival rate since planting

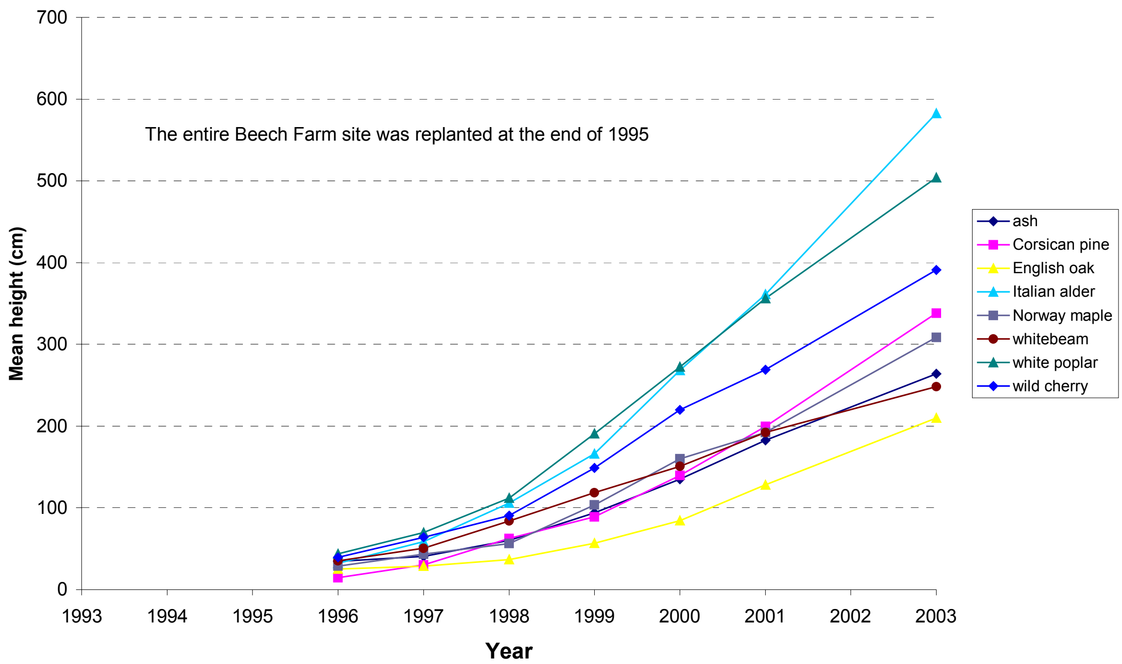
Species which have shown consistently good survival performance across most of the sites include whitebeam and white poplar, although it is interesting to observe a decline in survival rates of Corsican pine and white poplar at Pimbo since 1999. All species at Shaw Tip, with the exception of Leyland cypress, have maintained survival rates in excess of 70% of the original numbers planted. Ash and wild cherry demonstrated good survival performance to the wet, exposed conditions at Pimbo, whilst English oak and ash at the Yanley and Beech Farm sites and Norway maple at Beech Farm also retained a high stand number. Apart from whitebeam, most species at Grunty Fen have declined over the ten year period and only white poplar have shown any sign of stabilising, at a survival rate of approximately 55% by 2003. Grunty Fen is the most droughty of the sites and the poor survival results suggest that drought is a key factor limiting the longer-term survival of trees. Species which performed very poorly under these dry conditions include Japanese larch, Italian alder, English oak and ash. Exposure at Pimbo appears to have impacted heavily upon hybrid larch and to a lesser extent upon Corsican pine, while sycamore at this site did not establish well but has stabilised since 1997. The poor survival of Italian alder and wild cherry at Yanley and white poplar, Italian alder and Corsican pine at Beech Farm can be attributed to deer browsing.

There is no evidence to-date that the survival rate of the trees on the five sites has been affected by windthrow. It appears that young trees (of age up to seven or eight years and heights of up to 6 or 7 metres tall) 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. Neither has there been any evidence that generation of methane or landfill gas within the landfill is affecting tree survival at the sites.

2.5.2 Growth

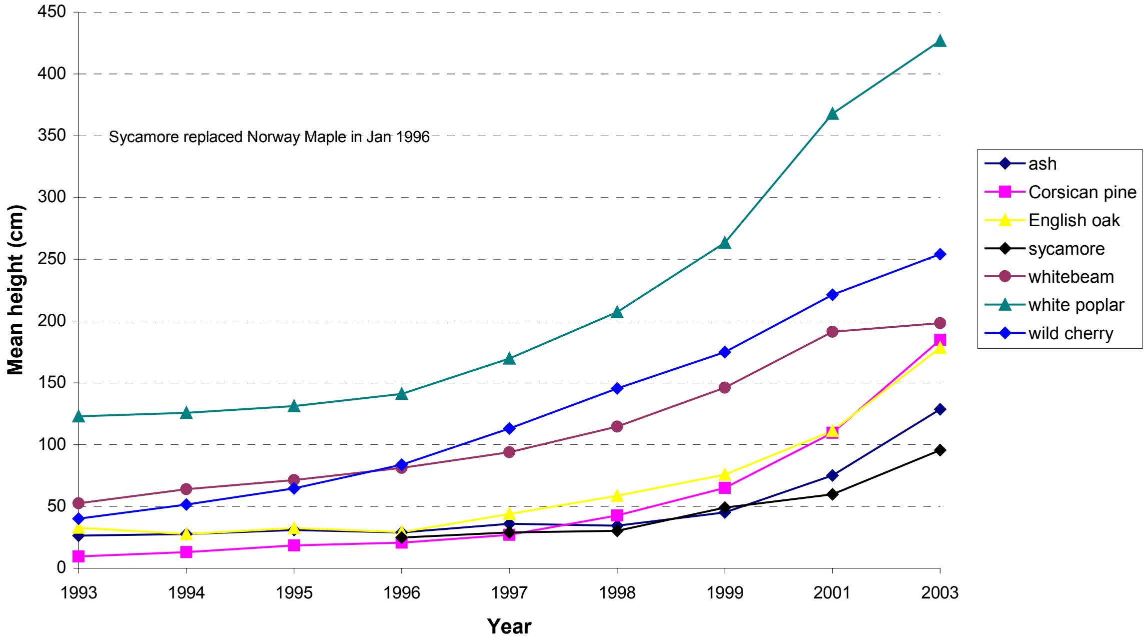
Tree growth was evaluated by means of annual measurements of height from 1994 to 1999 and then in 2001 and 2003, except at Beech Farm where annual observations were continued until 2001 due to replanting of the experiment. Figure 4 shows the height growth curves for different species at each of the sites. Figure 5 shows the same information expressed as the mean of annual incremental height changes for each of the species at each site. Data for 2000 to 2001 and 2002 to 2003 each represent two years of growth.

Figure 4 shows that Shaw Tip produced the fastest height growth rates for most species and that the slowest growth occurred at Grunty Fen, which is likely to have been the result of droughty conditions experienced there. Growth rates at Beech Farm steadily increased from 2000 and tree height at age 7 years is similar to that measured at Pimbo and Yanley in 1999. Across all sites, height growth rates appeared to be fastest in the poplar, alder, cherry, whitebeam and ash species. Species with slow growth rates included sycamore and oak. Nevertheless, care must be exercised in making comparisons between species with different growing habits. Climatic trends and varying physiological responses may also play a role in tree growth in these early years so it is difficult to isolate the impacts of landfill site conditions from other factors influencing growth rate.

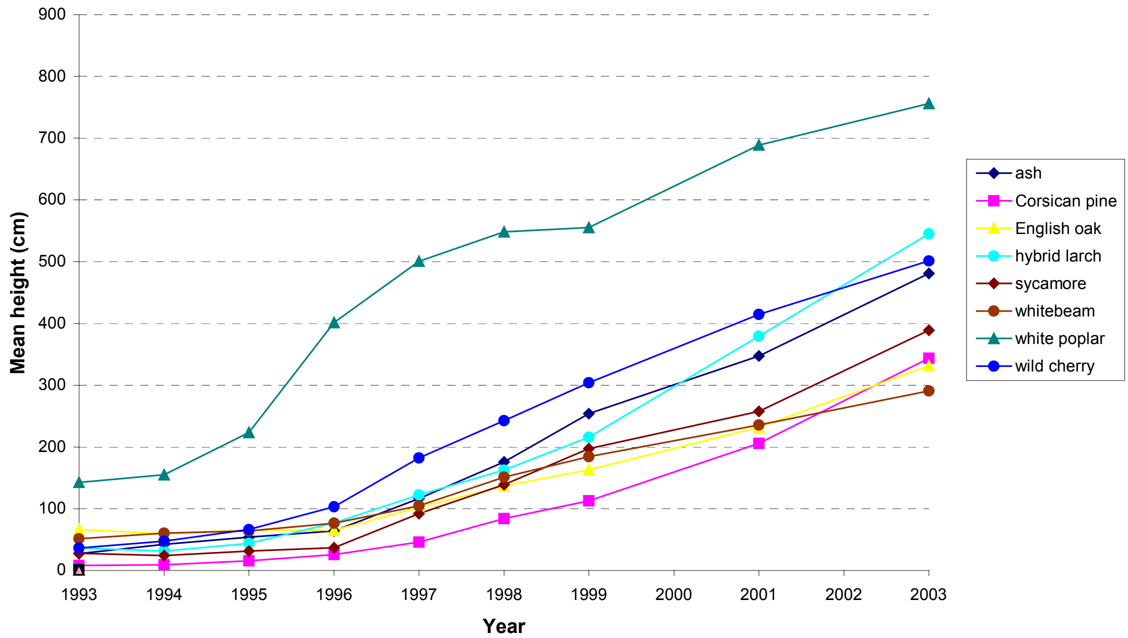


(a) Beech Farm (replanted end 1995)

Figure 4: Tree growth curves at the five landfill sites since planting

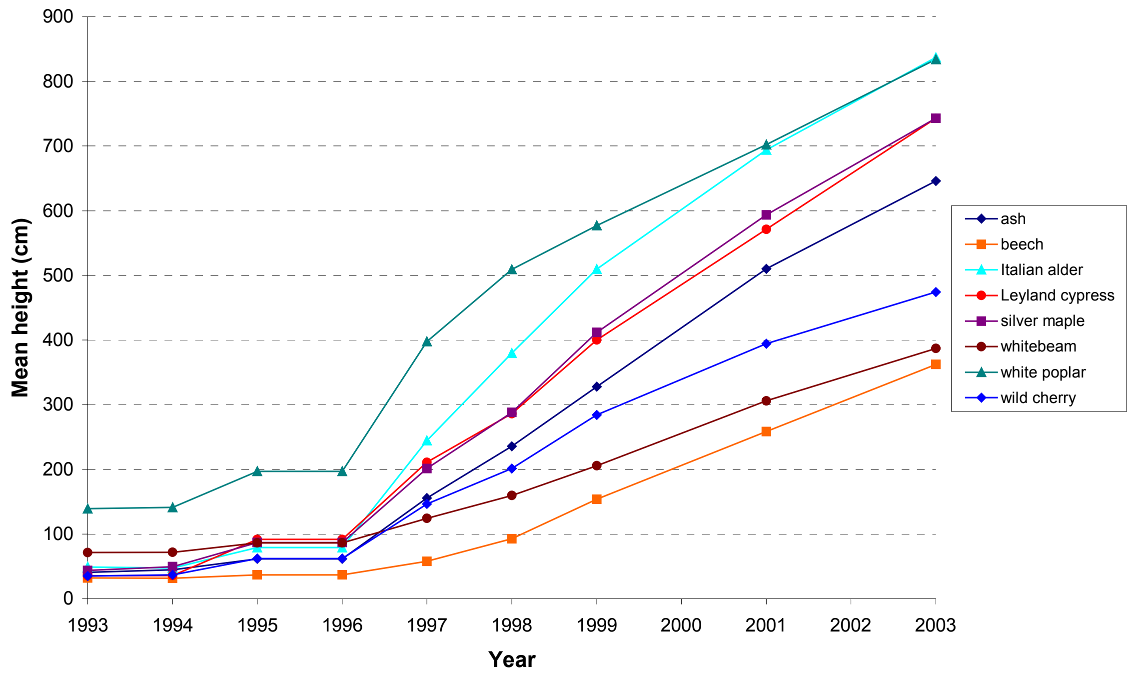


(b) Grunty Fen

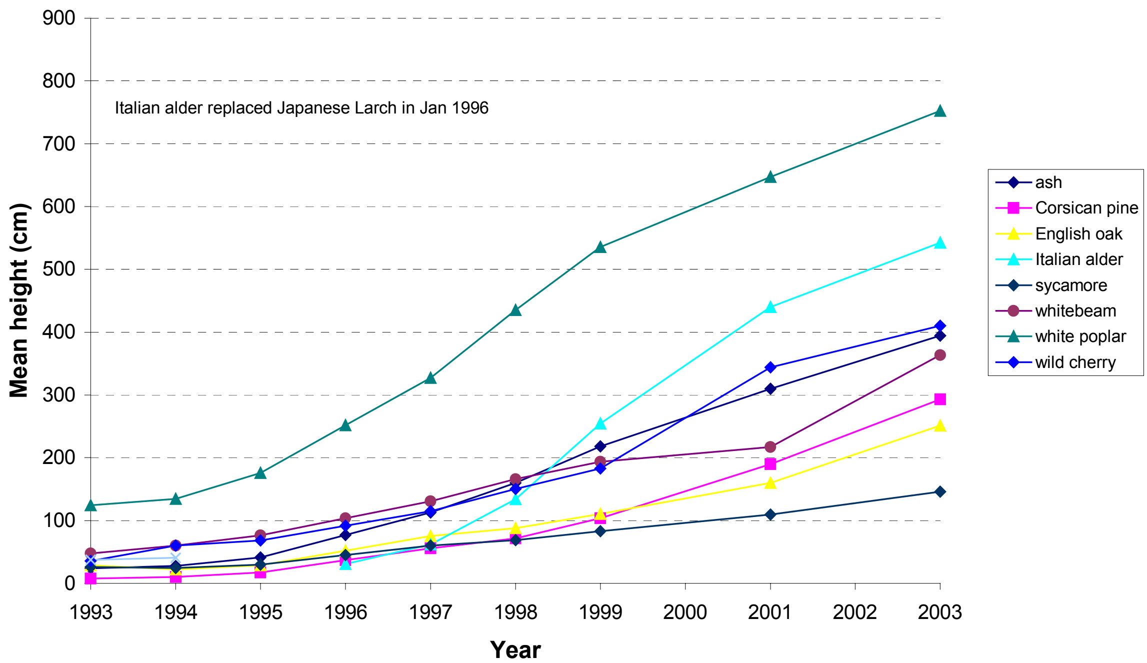


(c) Pimbo

Figure 4 cont'd: Tree growth curves at the five landfill sites since planting

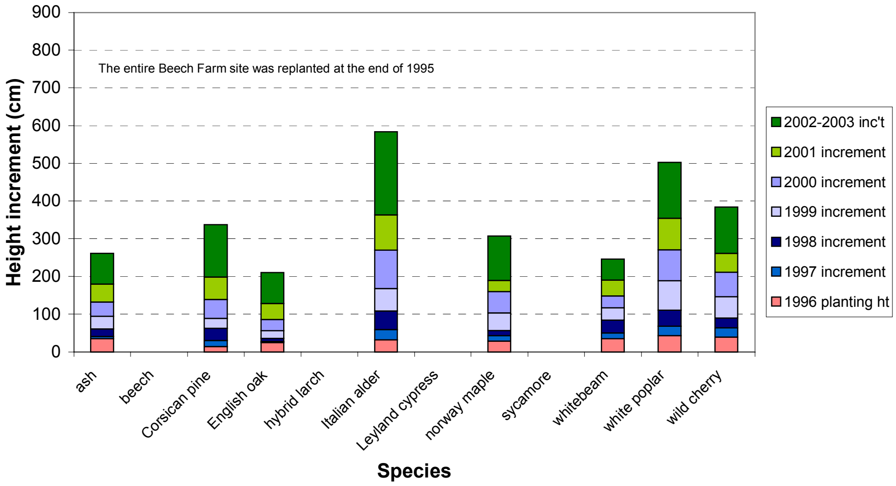


(d) Shaw Tip

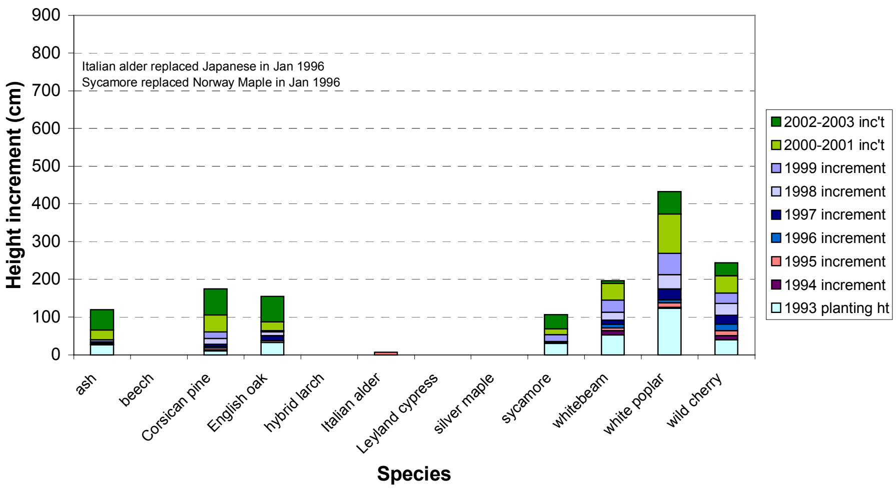


(e) Yanley

Figure 4 cont'd: Tree growth curves at the five landfill sites since planting



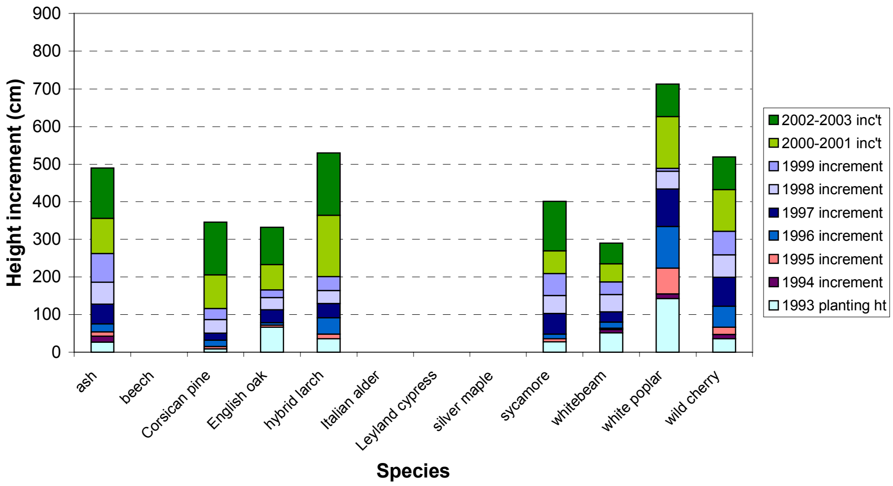
(a) Beech Farm



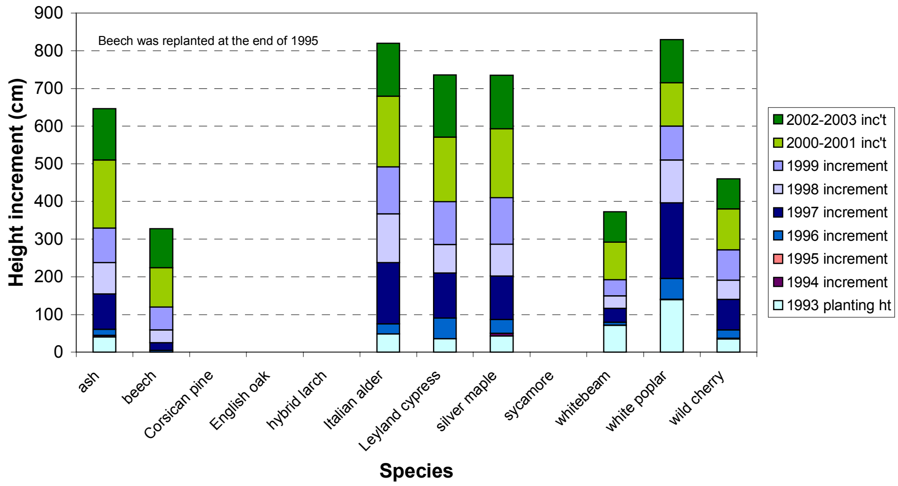
(b) Grunty Fen

Figure 5: Mean annual tree height increments at the five landfill sites since planting

(c) Pimbo



(d) Shaw Tip



(e) Yanley

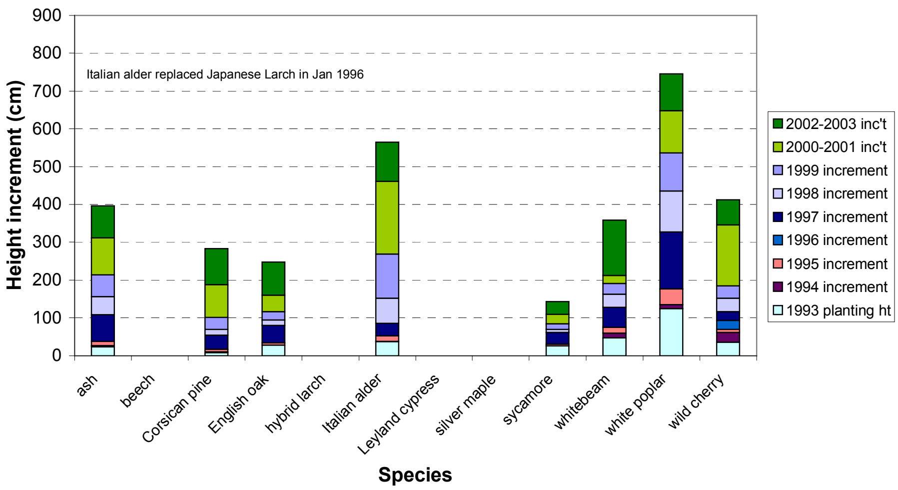


Figure 5 cont'd.: Mean annual tree height increments at the five landfill sites

Growth increments did not show steady annual increases and the performance of the same species planted at different sites was also markedly variable, which might reflect different climatic conditions or site conditions, such as soil moisture or nutrient status, in different years. It was also common for different species to demonstrate different rates and “spurts” of height growth due to physiological responses to site and climatic conditions in early years. However, annual increments at Grunty Fen appeared to be suppressed compared to the other sites, especially between 1994 and 1999 and tree growth rate showed little tendency to accelerate in more recent years at this site.

Table 3 indicates the period in which the annual incremental height growth of each species was at its maximum, compared between sites. The 2000-1 and 2002-3 increments (for all sites except Beech Farm) were divided by two to facilitate comparison with previous single year increments. However, these data should be treated with some caution since the numerical division assumes that growth rates in 2000 and 2001 and in 2002 and 2003 were the same.

Table 3: The year during which species achieved their maximum annual height increment

	Beech Farm	Grunty Fen	Pimbo	Shaw Tip	Yanley
ash	2001	2002-3	1999	1997	1997
beech	-	-	-	1999	-
Corsican pine	2002-3	2002-3	2002-3	-	2002-3
English oak	2001	2002-3	2002-3	-	1997
hybrid larch	-	-	2002-3	-	-
Italian alder	2000	-	-	1997	1999
Leyland cypress	-	-	-	1997	-
silver maple	2002-3	-	-	1999	-
sycamore	-	2002-3	2002-3	-	1997
whitebeam	2001	1999	1998	2000-1	2002-3
white poplar	2001	1999	1996	1997	1997
wild cherry	2000	1998	1997	1997	2000-1

Most species reached their maximum annual increment in 2000-1 or in 2002-3, which may reflect, in part, the fertiliser applications in 1999 and 2002. Examination of Figure 6, showing annual rainfall at three sites within reasonable proximity to Yanley (Long Ashton), Shaw Tip (Oxford) and Pimbo (Bradford), indicates that 1995 to 1996 were relatively dry years which may account for small increments in annual growth rate during this period. It is also possible that tree growth responded to the upturn in mean annual rainfall between 1997 and 2000. However, the decline in growth rate after 1999 during a higher rainfall period suggests that rainfall was not the limiting factor and trees may have experienced difficulties relating to inadequate moisture or nutrient storage within the soil cover. Figure 7 gives the summer (June, July and August) rainfall for the same stations. Summer drought in 1995 was very pronounced at all sites, which may explain why such poor height increments were experienced in the subsequent growth period. It was at this time when the trees planted at the Beech Farm trial plots failed and all species at this site were replanted in January 1996. The climatic trends suggest that it was not poor planting practice or maintenance that accounted for the poor tree survival and growth performance at this time but the unusually dry weather conditions.

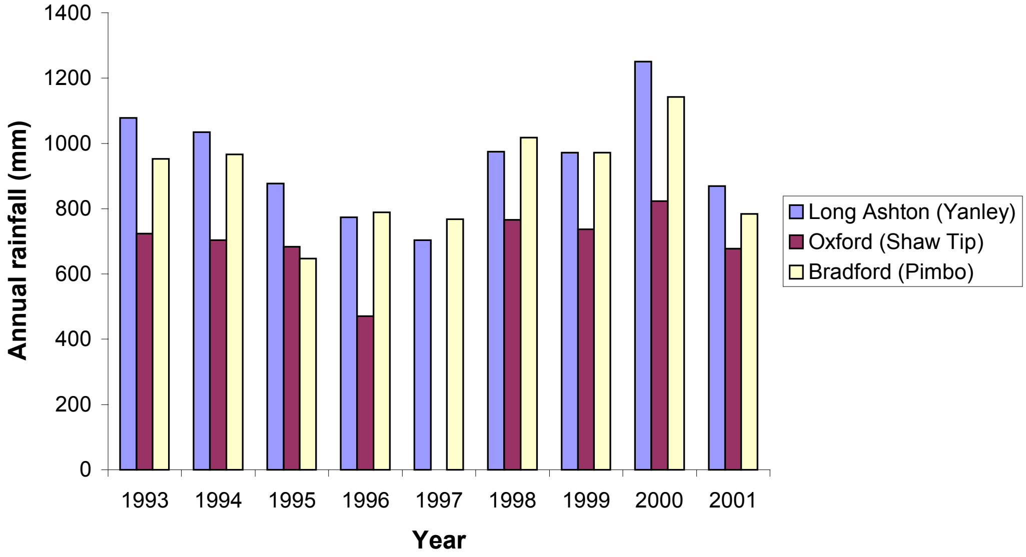


Figure 6: Mean annual rainfall for three stations near Yanley, Shaw Tip and Pimbo (Source: Meteorological Office). Note rainfall data for Oxford in 1997 are missing.

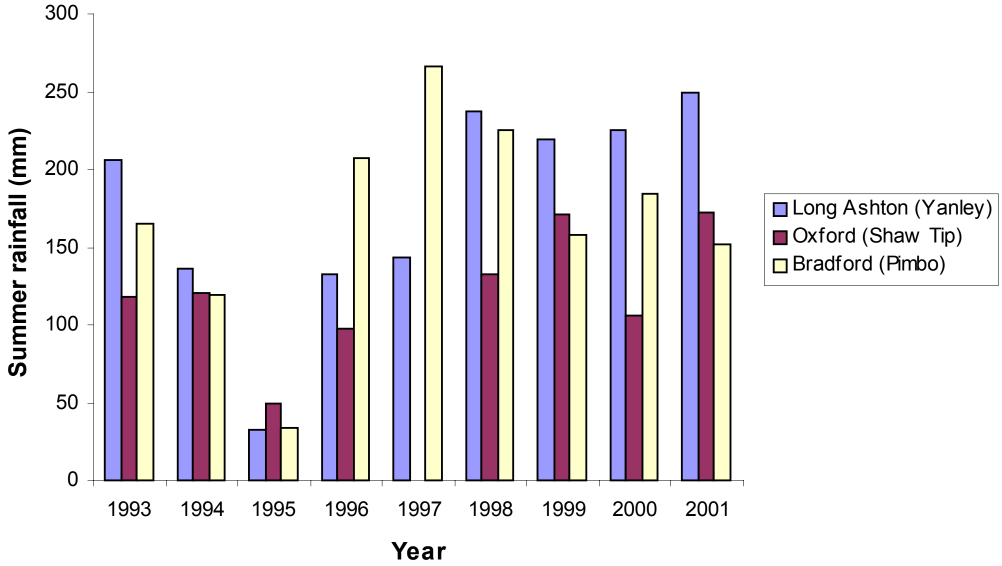


Figure 7: Mean summer rainfall for three stations near Yanley, Shaw Tip and Pimbo (Source: Meteorological Office). Note rainfall data for Oxford in 1997 are

Table 4 presents the Yield Class for selected species at year 10. Yield curves are typically applied in forestry practice to identify the growth performance or productivity of different species and the "Yield Class" defines the mean annual increment of the stand in volumetric terms as cubic metres of timber per hectare per year (as opposed to the mean annual increment in Figure 5 which depicts changes in height). Some tree species may have a relatively small height at year 10 (e.g. Corsican pine) compared to other species (e.g. poplar) but this does not provide a true picture of the potential productivity. The Yield Class gives a clearer indication of how well a species is performing against the potential that it might attain. Note that the Yield Class figures derived here (due to low plot numbers) are from *mean* overall stand height for each species, as opposed to the true definition of Yield Class which represents the mean height of the 100 tallest trees in a stand. Because trees at Beech Farm are younger than 10 years, no Yield Class data have been derived for this site.

Table 4: Measured and regional average Yield Classes (m^3 ha^{-1} $year^{-1}$) at Year 10 for all sites except Beech Farm. For explanation of Yield Class, see text above. na indicates Yield Class curves not available (trees < 10 years old) for these species.

Species	Grunty Fen		Pimbo		Shaw Tip		Yanley	
	measured	regional average	measured	regional average	measured	regional average	measured	regional average
ash	2	5	8	na	10	5	6	5
beech					10	7		
Corsican pine	6	15	16	14			12	16
English oak	4	5	8	7			6	5
hybrid larch			12	11				
Italian alder	na	na			12	6	na	na
Leyland cypress					24	15		
silver maple					10	7		
sycamore	na		4	6			2	5
whitebeam	4	na	6	na	8	na	8	na
white poplar	4	na	4	6	6	6	4	6
wild cherry	4	4	8	na	8	na	6	na

Comparing measured Yield Class data with regional averages derived from forests and woodlands on land undisturbed by mineral extraction or landfilling confirms the relatively poor performance of trees at Grunty Fen, and the impressive growth at Shaw Tip. The conifers naturally demonstrate a larger Yield Class than the broadleaves, and at Shaw Tip and Pimbo growth was better than average. Of the broadleaves, oak showed consistent growth closest to average expectations, though with only one or two exceptions (e.g. ash at Grunty Fen and sycamore at Yanley), growth of broadleaved species was reasonable given the generally hostile conditions at most sites.

Comparing the results for the period of maximum increment (Table 3) with the tree growth rates (Figure 4) suggests that the overall growth rate remained fairly constant over time but that individual species were experiencing limitations to growth, as indicated by low Yield Classes, particularly at Grunty Fen. This may be the result either of nutrient deficiency or perhaps limitations imposed upon the trees by conditions within the soil cover or due to the presence of the cap, which may include compaction and limited root extension, poor aeration, or more notably drought at the Grunty Fen site.

2.5.3 Nutrition

Foliar samples were collected from each site in August (deciduous species) and November (evergreens) in 1998 and 2001 and the data are presented in Table 5. The samples were analysed at the Forest Research Chemical Laboratories in Farnham. The experimental plots were fertilised with nitrogen (as urea) in spring 1999 and the 2001 results were used to interpret the nutrient status of the trees to identify if further fertiliser would be required.

Table 5 : Foliar nutrient status at the landfill sites

Nitrogen status

Species	Beech Farm		Grunty Fen		Pimbo		Shaw Tip		Yanley		Deficient	Optimum
	1998	2001	1998	2001	1998	2001	1998	2001	1998	2001	(% dry wt)	(% dry wt)
ash	- -	- -	- -	- -	- -	- -	- -	-	-	- -	<2.0	>2.3
beech							- -	- -			<2.0	>2.3
Corsican Pine	-	- -	- -	- -	- -	- -			-	-	<1.2	>1.5
English oak	- -	- -	- -	- -	-	-			- -	- -	<2.0	>2.3
hybrid larch					- -	-					<1.8	>2.5
Italian alder	no data	+	no data	- -			+	-	- -	+	<2.5	>2.8
Leyland Cypress							- -	- -			<1.2	>2.3
silver maple	-	- -					- -	- -			<2.0	>2.3
sycamore			no data	- -	- -	- -			- -	- -	<2.0	>2.3
white poplar	+	-	-	- -	+	+	-	+	-	+	<2.0	>2.3
whitebeam	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	<2.0	>2.3
wild cherry	-	- -	-	- -	-	- -	- -	- -	-	- -	<2.0	>2.3

Phosphorus status

Species	Beech Farm		Grunty Fen		Pimbo		Shaw Tip		Yanley		Deficient	Optimum
	1998	2001	1998	2001	1998	2001	1998	2001	1998	2001	(% dry wt)	(% dry wt)
ash	+	-	- -	+	+	+	+	+	+	+	<0.19	>0.22
beech							-	- -			<0.14	>0.16
Corsican Pine	-	-	- -	- -	-	-			- -	-	<0.12	>0.16
English oak	+	+	- -	+	+	+			- -	+	<0.14	>0.16
hybrid larch					+	+					<0.18	>0.25
Italian alder	no data	- -	no data	+			-	- -	- -	+	<0.16	>0.18
Leyland Cypress							+	+			<0.12	>0.16
silver maple	+	+					-	-			<0.19	>0.22
sycamore			no data	+	+	+			+	+	<0.17	>0.20
white poplar	+	+	+	-	+	+	+	+	+	+	<0.17	>0.20
whitebeam	+	+	+	+	+	+	+	+	+	+	<0.17	>0.20
wild cherry	+	+	+	+	+	+	+	+	+	+	<0.17	>0.20

Potassium status

Species	Beech Farm		Grunty Fen		Pimbo		Shaw Tip		Yanley		Deficient	Optimum
	1998	2001	1998	2001	1998	2001	1998	2001	1998	2001	(% dry wt)	(% dry wt)
ash	+	+	+	+	+	+	+	+	+	+	<0.7	>0.9
beech							- -	- -			<0.7	>0.9
Corsican Pine	-	+	-	-	-	-			-	-	<0.3	>0.5
English oak	+	-	-	+	-	-			+	+	<0.7	>0.9
hybrid larch					+	+					<0.5	>0.8
Italian alder	no data	- -	no data	+			+	-	+	+	<0.7	>0.9
Leyland Cypress							+	+			<0.3	>0.5
silver maple	+	+					+	+			<0.7	>0.9
sycamore			no data	+	-	+			+	+	<0.7	>0.9
white poplar	+	+	+	-	+	+	+	+	+	+	<0.7	>0.9
whitebeam	+	+	+	+	+	+	+	+	+	+	<0.7	>0.9
wild cherry	+	+	+	+	+	+	+	+	+	+	<0.7	>0.9

- - **deficient** - **slightly deficient** + **optimal** tree species absent

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 remaining 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; Callan and Westcott, 1996; Ystaas *et al*., 1997). This information was combined with that in Taylor (1991) to estimate deficient and optimal values for those species where no data are available. The appropriate values for optimum and deficient nutrition status are presented in Table 5 for nitrogen, phosphorus and potassium.

Each species at the five sites were defined as deficient, marginal or optimal for N, P and K. The results (Table 5) demonstrate that nutrient shortage was most severe in the case of nitrogen, with most species demonstrating severe deficiency at two or more sites. Only white poplar and Italian alder demonstrated instances of optimal nitrogen status and this did not occur on all sites, while the remaining species typically exhibited signs of deficiency. Wild cherry, which was coping reasonably with nitrogen shortage in 1998, showed signs of severe deficiency in 2001. These results generally agree with the growth data discussed above and may explain the observed slowing of growth rate in some species in 2000 to 2001. Italian alder might be expected to show less of a nitrogen deficiency than other species because of its atmospheric nitrogen-fixing capability. However, nitrogen fixation does not provide the tree with all of the nitrogen it needs (Hood, 1993) which may explain why alder still exhibited slight or severe nitrogen deficiency at some sites. It is also possible that some alder were poorly nodulated and thus were unable to 'fix' nitrogen. A re-application of nitrogen fertiliser was made in spring 2002 and a small growth spurt or maximum annual increment in 2002–3 was identified in some species (Table 3) which might be attributed to the addition.

Phosphorus and potassium were generally optimal under whitebeam, sycamore, poplar, cherry and ash but showed some deficiency in other species. Corsican pine appeared to be deficient in phosphorus and potassium at most of the sites. Lack of phosphorus may limit growth, although the year 10 Yield Class data for Corsican pine do not reflect this assumption, except perhaps at Grunty Fen. Oak and beech also exhibited slight or moderate deficiencies in potassium. The foliar data confirm that potassium supply is generally not a problem for woodland establishment on brownfield sites (Moffat and McNeill, 1994). With a probable nitrogen deficiency, however, some species may be difficult to establish on landfill (and other brownfield) sites without application of a compound inorganic or organic fertiliser containing phosphorus.

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. In 2001, only four had optimal supply of all three nutrients, despite a nitrogen application in spring 1999; species include poplar at Pimbo, Shaw Tip and Yanley, and Italian alder at Yanley.

The deficiencies identified in the 2001 foliar analysis demonstrate the temporary effect of artificial mineral fertiliser application to the types of substrates used in the landfill experiments. It is likely that considerable loss of nutrients has occurred, especially of nitrogen, by leaching in these soils very poor in organic matter content. Reclamation of these soil materials in 1993-4 pre-dated guidance on the use of 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 the five landfill sites would appear to confirm the applicability of this guidance, in that supplementary fertiliser application again seemed warranted only three years after the first application. Reliance upon the regular and continued application of mineral fertiliser to maintain stand growth and condition does not support sustainability principles. Instead, sites should be prepared with amendments of organic waste materials if soil-forming materials are used for reclamation purposes.

2.6 SUMMARY

The tree survival data show a clear difference between performance in the early years, which is likely to be related to tree stocking, planting conditions and weed control, compared to the steady survival performance of species in later years which is indicative of a stabilised survival condition. White poplar, whitebeam and ash give the best survival rates. The first three years are critical in defining the ability of tree species to survive at any particular site, but mortality may continue in some species well beyond the 'establishment period'.

Tree growth performance between species was variable in the first ten years but white poplar, Italian alder, whitebeam, wild cherry and, where moisture availability was not limiting, ash were the most successful species. It is difficult to compare performance between species, however, since growth responses may reflect species rooting and growth habit as well as site conditions. Hence, of the conventional woodland species, Corsican pine appears to be performing the best in terms of yield performance, even though the measured tree height achieved after ten years is moderate compared to other species.

Drought appears to be an important factor limiting tree growth, as seen by the overall results for Grunty Fen and the depressed annual growth rates in the years of drier summers from 1995 to 1996, at all sites. Foliar results also indicate that trees are experiencing deficiency in nitrogen and phosphorus, which may help to account for a decline in growth rate since 1999 despite relatively high and sustained annual rainfall rates.

Taken together, the results of the field experiments suggest that it is perfectly possible to establish woodland composed of tree species that grow reasonably well compared with equivalents established on greenfield sites. The experiments generally support previous guidance on woodland establishment on landfill sites (Dobson and Moffat, 1993; Bending and Moffat, 1997). From an engineering standpoint, the results reinforce the need for uncompact, rootable soil or soil-forming material, preferably placed by loose tipping or 'complete cultivation'. The widespread nitrogen deficiency detected during the monitoring programme was predictable given the infertile materials used in restoration at most sites. However, there was no opportunity to follow guidance given in Dobson and Moffat (1993) (and amplified by Bending *et al*., 1999), that organic waste materials such as sewage sludge be applied to the sites as an overall treatment. The inability of artificial mineral fertilisers to redress permanently nutrient deficiency in the field experiments underlines the need for this alternative, and more effective approach to restored land amendment.

Proper attention to provision of a suitable thickness of soil or soil-forming material, prevention of compaction and site fertility can therefore maximise the likelihood of good tree performance. However, the field experimentation programme also highlighted the influence of climate, in particular rainfall. For some parts of the country, notably the drier south and east, meticulous weed control is increasingly necessary, but even if undertaken effectively, there remains a risk to tree survival and performance on those sites where plant available water may be limited, for example at sites like Grunty Fen where low rainfall combined with a clayey substrate of relatively low available water capacity. The potential influence of climate change was 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 UKCIP02 climate change scenarios (Hulme *et al*., 2002).

Species choice is an obvious way to maximise the likelihood of a successful woodland, and the field experimental programme has demonstrated that some tree species tested are more robust and/or provide a low risk of failure. These have been discussed above. Other tree species, especially 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 far as possible, and to be conservative in the expectations for the new woodland, e.g. not to expect 'climax' woodland species to thrive on unamended soil-forming materials. However, the climate change scenarios referred to above make 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; Broadmeadow and Ray, 2005). In these regions, notably drought-tolerant species should be chosen. Some species, such as white poplar may perform well as a response to climate change (Cannell *et al*., 1989), but others such cherry may fare less well than today. It may also be necessary to consider species not tested in these experiments, such as walnut (*Juglans nigra*), holly oak (*Quercus ilex*) and *Eucalyptus* spp. and *Nothofagus* spp. Such species are, of course, non-natives to the British Isles.

The trees on the experimental sites are relatively young (only ten years old), and the interaction between tree rooting and the landfill cap environment is expected to become more complex as the trees grow and mature and begin to encounter further limitations to growth. Despite the uncertainty that climate change may bring, the five tree species experiments are a very 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. More reliable information on both these issues will become available as the monitoring plots mature.

3. IMPACT OF TREE ROOTING ON CAP INTEGRITY AT WATERFORD LANDFILL SITE

3.1 INTRODUCTION

This chapter summarises the main findings of the experiment conducted at Waterford to examine the degree of rooting into landfill caps. This field-based research was conducted in 1997 and again in 2002 to examine the impact of soil cover depth and landfill cap conditions on tree rooting for trees planted in 1986, and aged 11 and 16 at the time of the two studies.

3.2 OBJECTIVES

The landfill cap experiment had four objectives:

1. To examine the pattern of tree performance and root growth at the Waterford landfill site in soil covers of different depth.
2. To assess the interaction between tree roots, the soil cover and the landfill cap for four tree species and for a range of soil cover depths.
3. To identify the key factors influencing or preventing root penetration or extension into the cap, including soil / cap conditions and tree rooting habit.
4. To compare the tree rooting condition in 1997 and 2002 and examine the conditions required for tree planting over landfill caps in order to retain cap integrity.

3.3 THE STUDY SITE

The investigation was conducted at the Brett Aggregates Ltd Waterford landfill site in Hertfordshire (National Grid Reference TL 307147). The site was formerly opencast quarried for sand and gravel. The resulting void space was filled with domestic waste and inert fill and restored in 1985 to modern landfill standards, including the provision of passive landfill gas venting and an engineered mineral cap of approximately 1 m thickness. Methane generation indicated a significant biodegradable component to the waste and Brett Aggregates were in the process of installing an engineered gas well system across the site during the summer of 2002. However, there was no evidence that this physically affected the landfill cap, soil or trees in the study plots (see below).

Soil-forming materials derived from silt-bed deposits (sand and gravel washings) were placed over the landfill cap using the loose-tipping method. These materials were placed in ridges transverse to slope to achieve a successful forestry plantation (Fourt, 1980). Ridges were approximately 30 m wide and 1.5 m high at their central point. Soil thickness across the ridges at the time of the 2002 study, after some resettlement, varied between 1.3 metres at the crest to 0.45 metres at the outer edge of the ridge. This enabled the effect of ridge position and the influence of soil cover thickness over the landfill cap on rooting to be investigated.

In the dominantly silty textured soil-forming material, 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).

Four tree species were planted in 1986: ash (*Fraxinus excelsior*), alder (*Alnus* spp.), sycamore (*Acer pseudoplatanus*) and Corsican pine (*Pinus nigra* var. *maritima*). Trees were planted at two metre intervals with rows of each individual tree species running along the length of the ridges. The 1997 study examined the rooting characteristics of three of the species: alder, Corsican pine and sycamore. In the recent 2002 study, the rooting condition of all four species was examined.

The site is south-facing and sloping, with an average gradient of 7-8º 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). Low-lying parts of the site tend to suffer from periodic waterlogging although the restored soil profile in the middle and upper parts of the ridges appeared to be freely draining, which may be due to the low bulk density produced by loose tipping and the ability to transmit water laterally.

3.4 METHODS

The rooting studies generally followed the same procedure as for the May 1997 work. Transect lines were surveyed at three positions on each ridge corresponding to the crest line (approximately 1.3 m soil cover), the mid-slope (approximately 1.0 m soil cover) and the outer edge or basal ridge position (approximately 0.5 m soil cover). In the 1997 study, between three and five trees of each species were selected for each ridge position on one ridge, giving 36 sample trees. In 2002, between two and six trees of each species were selected for each ridge position (depending on access) but located over three ridges, giving 41 sample trees. Rooting studies were conducted in July and September 2002 on trees exhibiting vigorous growth, purposefully avoiding suppressed trees.

There were two main reasons for the different approach to tree selection in 2002 compared to the 1997 study:

1. The method reduced the risk of excavating pits in 2002 which might be located on ground disturbed during the 1997 intrusive work.
2. The selection of trees for study was hampered by difficulties in accessing the trees with the mini-digger used for the root excavation work. Many parts of the ridges (especially at the crest) were inaccessible to the mini-digger due to increases in tree height, diameter and branching since the 1997 survey. 28 trees were examined in July 2002, mostly on the shallower outer or mid-ridge positions. Some selected felling was conducted in August 2002, with the permission of Brett Aggregates Ltd, to improve access to the centre of the ridges and the rooting systems of additional trees located at the ridge crest on the deeper soils were investigated in September 2002. However,

accessibility controlled the number of replicates of each tree species that could be assessed at each ridge position or soil cover depth.

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 July and in September 2002. 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.

In both the 1997 and 2002 studies, trenches were excavated to 20 cm below the cap/substrate interface for each tree examined. 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 carefully 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 Plate 1). The co-ordinates of each root were then noted and the root diameter (at the point where the root emerged from the soil face) 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.

Plate 1: Example of the root evaluation procedure using pegs

Where roots were identified to be penetrating into the cap, further excavation deeper into the cap was conducted to identify the maximum depth of root penetration. This was achieved by carefully digging away the cap material surrounding each root using a knife and working down the root channel until the tip of the root was reached. The location of the root tip and its diameter were recorded using the method described above. Maps of root distribution were generated using Surfer software (Golden Software, Inc.).

A total of 41 samples of soil cover material were collected for bulk density determination in 2002. Samples of the soil were taken at approximately 25 cm thickness intervals to 1.2 m depth from eight trenches located 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 using the Hodgson (1997) method. The landfill cap was too dense and stony for the coring method to be used so the bulk density of the landfill cap material was obtained by excavating nine clods and determining their volume using the displacement method (British Standards Institution, 1990). The mass of the clods was determined by oven-drying and weighing. Stones larger than 2 mm were removed from each sample by wet-sieving and the mass to displacement volume procedure was repeated on the stone fraction. The bulk density of the < 2 mm fraction of the clods was then calculated by subtracting the stone mass and volume from the total sample mass and volume.

To examine the microstructure of the landfill cap and study how tree roots had penetrated into it, twelve undisturbed samples were removed from the cap. Ten of the samples were taken at a depth of 10-15 cm, just below the cap/soil interface. Two of the samples were collected from a depth of 95 cm below the soil / cap interface; both contained alder rooting and represented the greatest depth of penetration of rooting into the cap. 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 thin sections at different scales of resolution including macro and micro (refer to Annex 2 by Mooney, 2004, for specific methodological details). Images were first assessed on a macro scale using descriptive techniques and then by collecting a standard 1320 x 820 resolution ".jpeg" image from each thin section at a spatial resolution of 1 pixel = 72 μm. Image analysis was conducted using AnalySIS software (SIS Systems, Germany) in order to calculate total porosity, pore area (number of pixels comprising a discrete pore), pore sphericity (a measure of pore roundness) and pore roughness. Further detail regarding these measurements can be found in Mooney *et al*. (2000). Micro-analysis was conducted using a Zeiss high powered polarising microscope. The thin sections were examined and described at several magnifications, and several photomicrographs of each thin section were collected at a magnification of x 25 (1 pixel = 2.5 μm) as a 1200 x 800 resolution ".tif" image. One micro-image from each thin section was chosen for image analysis (as for macro-analysis) to measure the same porosity features.

3.5 RESULTS AND DISCUSSION

3.5.1 Tree rooting profiles and the role of soil cover depth

Table 6 and Table 7 show summary data for 2002 and 1997, respectively, for each individual tree examined. The tables indicate the tree height, the depth of soil cover above the cap at each location, the total number of roots and the maximum rooting depth from the soil surface. The "cap horizontal rooting density" refers to the density of rooting across the 1 metre horizontal width (the x axis) of the examined profile and measured from the soil / cap interface down to a depth of 1 metre into the cap.

The maximum depth of rooting within the cap, measured as a vertical distance from the soil / cap interface, and the diameter range of roots within the cap are also presented. Examples of the root

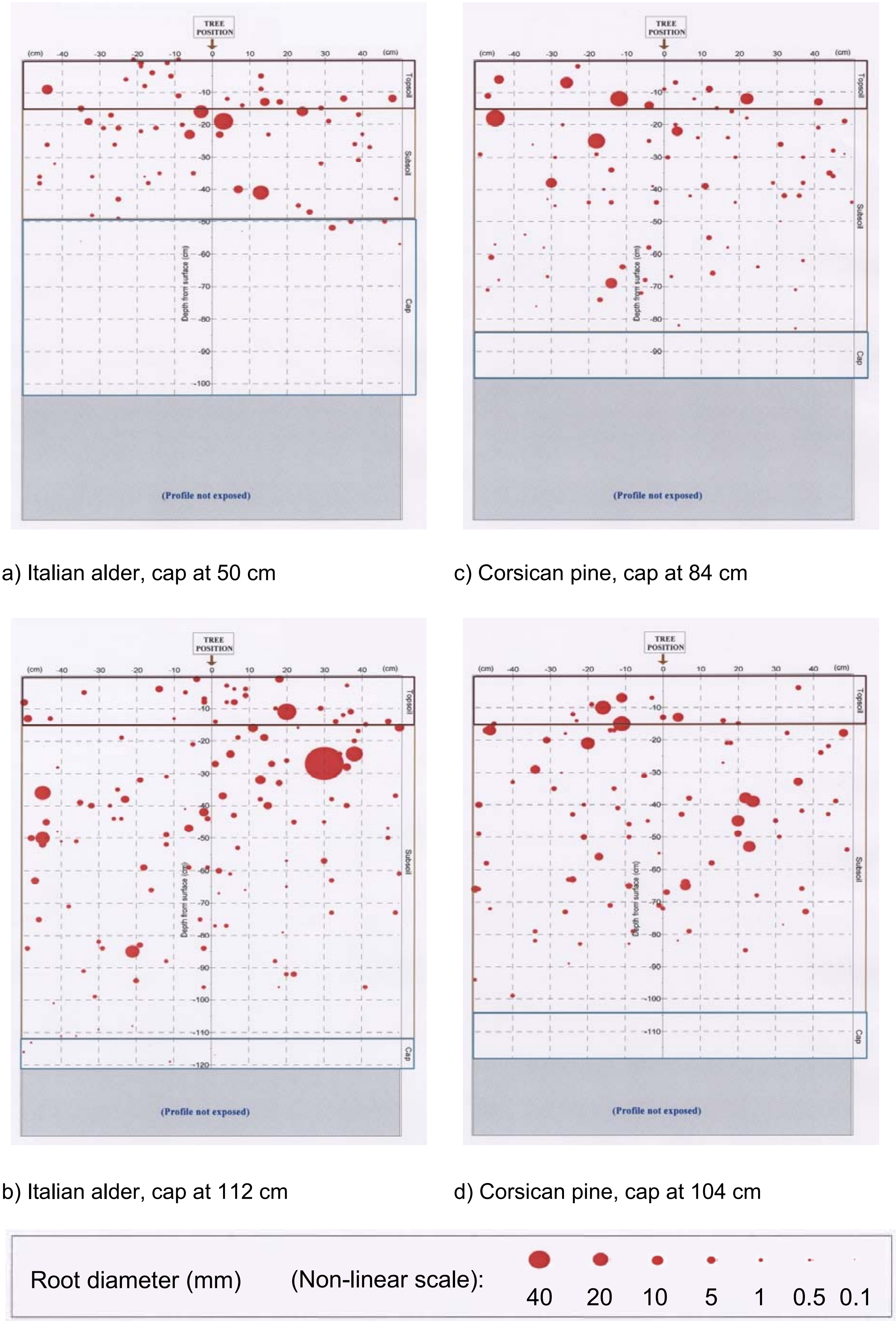
Species	Tree height (m)	Depth of soil above cap (cm)	Total number of roots	Number of roots within 3 cm of the cap	Number of roots breaking the cap	Max. rooting depth (cm)	Cap horizontal rooting density (no. m^{-2})	Cap root diameter range (mm)	
								min	max
alder	8.2	49	68	12	9	60	7	0.1	3.9
	8.1	78	56	5	4	176	5	0.2	3.8
	7.6	83	54	1	0	81	0	-	-
	7.6	93	97	1	0	91	0	-	-
	7.7	106	113	0	0	93	0	-	-
	7.9	106	91	19	9	118	12	0.2	11.4
	8.7	112	93	10	2	119	4	0.2	0.4
	8.0	112	130	7	4	119	4	0.1	0.3
	8.3	113	137	7	0	141	7	0.1	0.2
	7.9	120	86	3	2	143	5	0.1	1.8
	7.8	130	300	1	0	127	0	-	-
ash	7.1	54	79	12	1	55	0	1.2	1.2
	7.8	65	86	15	12	76	13	0.2	2.8
	6.7	94	93	0	0	72	0	-	-
	6.9	97	81	0	0	71	0	-	-
	7.9	106	114	3	2	107	2	1.5	3.0
	7.6	107	56	0	0	97	0	-	-
	6.8	110	75	0	0	105	0	-	-
	6.8	114	54	0	0	103	0	-	-
	7.5	116	87	13	6	121	3	0.1	1.6
	6.8	119	153	11	4	123	4	0.1	0.5
	7.3	120	266	0	0	112	0	-	-
	8.0	125	235	0	0	113	0	-	-
Corsican pine	8.0	84	79	2	0	83	0	-	-
	6.9	88	139	15	0	88	0	-	-
	7.3	99	37	0	0	81	0	-	-
	7.2	104	88	0	0	99	0	-	-
	7.5	105	94	14	7	110	7	0.1	1.0
	7.6	108	69	5	2	115	2	0.5	1.0
	8.1	110	67	0	0	105	0	-	-
	8.0	122	483	0	0	109	0	-	-
	7.7	123	631	0	0	108	0	-	-
	7.8	132	358	0	0	127	0	-	-
sycamore	5.6	75	88	17	12	141	15	0.1	6.6
	6.1	83	42	0	0	79	0	-	-
	5.8	85	53	6	5	96	5	0.2	0.8
	6.0	91	70	0	0	77	0	-	-
	6.2	100	73	18	15	110	15	0.1	2.4
	5.9	105	59	0	0	100	0	-	-
	6.0	106	76	0	0	95	0	-	-
	6.3	108	145	5	1	108	1	0.5	0.5

distribution plots for the four species in 2002 are presented in Figure 8.

Table 6: Summary of individual profile examinations, 2002

Table 7: Summary of individual profile examinations, 1997

Species	Tree height (m)	Depth of soil above cap (cm)	Total no. of roots	Maximum rooting depth (cm)	Cap horizontal rooting density (no. m^{-2})	Maximum rooting depth into cap (cm)	Cap root diameter range (mm)	
							min	max
alder	5.7	57	22	87	14	30	1.5	5.0
	7.1	61	24	67	14	6	1.0	3.0
	6.3	67	37	77	8	10	1.5	5.0
	5.5	71	19	82	12	11	1.5	3.5
	4.9	71	33	83	24	12	1.5	4.5
	5.8	100	31	102	6	2	1.0	2.0
	6.1	100	43	102	4	2	1.5	2.0
	5.9	100	25	91	0	0	-	-
	7.0	102	18	89	0	0	-	-
	7.4	114	17	110	0	0	-	-
	5.7	118	20	112	0	0	-	-
	6.3	119	39	90	0	0	-	-
	7.1	133	22	96	0	0	-	-
Corsican pine	4.6	55	11	56	8	1	0.5	1.0
	4.0	58	11	56	0	0	-	-
	5.2	68	25	70	12	2	1.0	2.0
	4.4	70	16	72	8	1.5	1.0	1.5
	4.8	82	26	70	0	0	-	-
	3.1	98	24	95	0	0	-	-
	5.0	100	21	101	4	1	0.5	1.0
	4.5	105	19	90	0	0	-	-
	4.9	120	16	53	0	0	-	-
	4.5	124	22	92	0	0	-	-
	4.1	125	27	124	0	0	-	-
	4.3	125	19	80	0	0	-	-
	5.1	127	31	93	0	0	-	-
sycamore	3.5	62	18	62	0	0	-	-
	2.0	63	17	65	10	3	1.0	2.5
	2.9	64	16	63	0	0	-	-
	2.6	65	17	64	0	0	-	-
	3.7	100	28	101	8	1	0.5	1.0
	4.0	102	21	85	0	0	-	-
	5.1	110	26	96	0	0	-	-
	3.6	115	20	74	0	0	-	-
	4.0	117	17	99	0	0	-	-
	3.0	122	15	78	0	0	-	-
	6.0	132	35	132	0	0	-	-



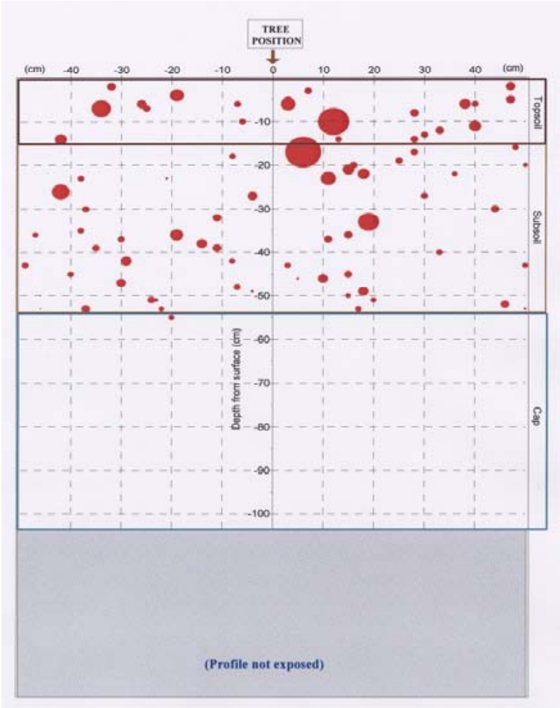
a) Italian alder, cap at 50 cm

c) Corsican pine, cap at 84 cm

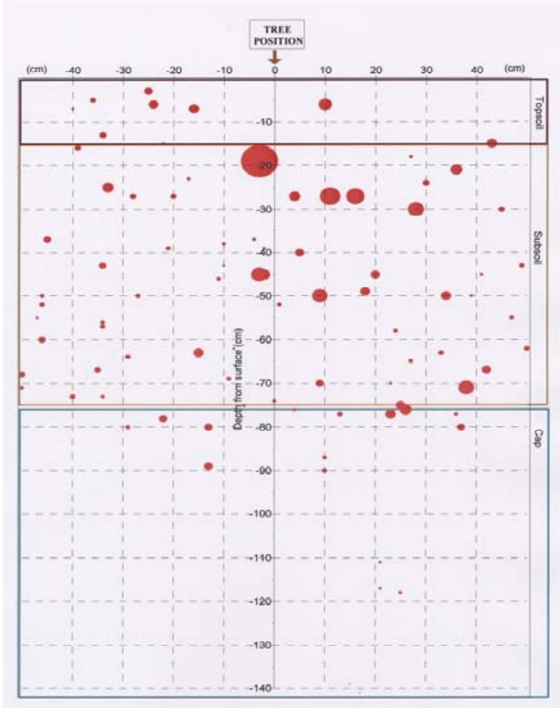
b) Italian alder, cap at 112 cm

d) Corsican pine, cap at 104 cm

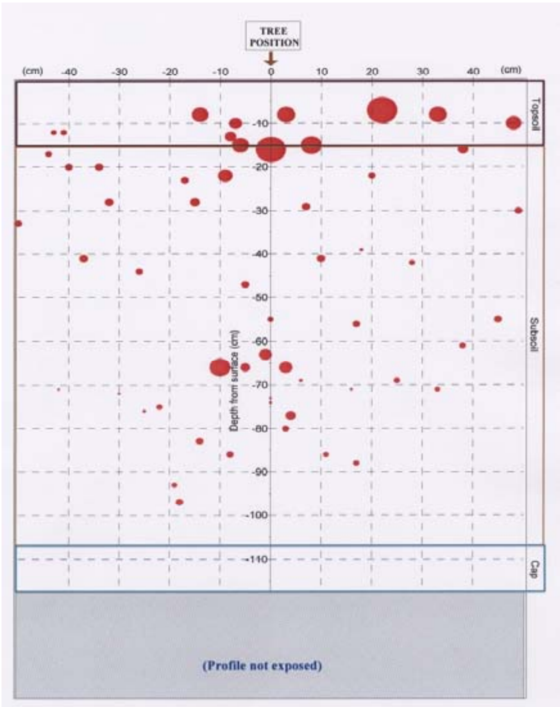
Figure 8: Examples of tree root distributions relative to cap depth



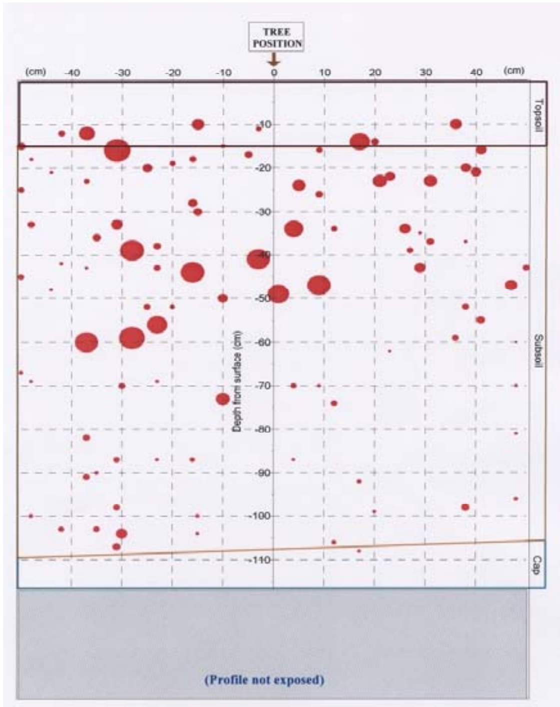
e) Ash, cap at 54 cm



g) Sycamore, cap at 76 cm



f) Ash, cap at 107 cm



h) Sycamore, cap at 108 cm

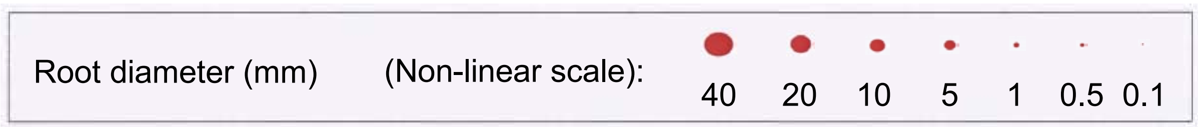


Figure 8 contd.: Examples of tree root distributions relative to cap depth

Statistical analysis was first conducted on the overall data set to identify broad differences in rooting characteristics between 1997 and 2002. Compared to 1997, the trees had significantly ($p < 0.001$) higher root counts in 2002 and this is also reflected in the values for mean root count per tree. Total root count was 848 for 35 trees in 1997, compared to 5255 for 41 trees in 2002. Sycamore and alder had on average three to four times the number of roots in 2002 than in 1997, whilst Corsican pine had over nine times, a number significantly influenced by three trees with large number of roots. There was also a significantly ($p < 0.05$) higher content of fine to very fine roots (diameter less than 0.5 mm) in 2002. This might be expected due to the branching and hierarchical nature of the rooting system and may also reflect tree physiological responses to site conditions (e.g. induced fine root production in response to soil moisture and nutrient stresses). It may also be a function of differences in the rooting evaluation procedure between years, since it is possible that some very fine roots may have been present in 1997 which were not measured. Some difficulty was encountered in observing the location and measuring the diameter of very fine roots, and very close and detailed profile examination is required.

Further examination of the 2002 data was conducted to identify if there were any relationships between rooting pattern or distribution and species characteristics or site factors. The effect of cap depth on numbers of roots is difficult to assess with five trees (3 Corsican Pine, 2 ash and 1 alder) in 2002 having a remarkably large number of roots. If these data are excluded then there is little effect of cap depth but if included root numbers are higher when depth to cap is greater than 120 cm. Another major difference between 1997 and 2002 was that in 1997 a lower percentage of roots had yet to approach within 3 cm of the cap and hence have the opportunity to enter it.

The potential for roots to penetrate into the cap requires that the root is first present at close proximity to the soil / cap interface. Only in alder did roots regularly approach the cap (10 out of 11 trees). For all four tree species, roots of several trees approached within 3 cm of the soil / cap interface but these appeared to be unrelated to total root count or depth of soil over the cap, although there is some evidence that fewer roots are found within 3 cm of the cap at soil thicknesses greater than 120 cm. This suggests that other factors such as the degree of compaction in the material overlying the cap are likely to be important in determining the number of roots reaching the cap. Figure 9 highlights the relationship between maximum rooting depth and depth to cap for 2002 data. The wide scatter of data points on both sides of the dotted line (cap depth) indicates that almost half of the examined profiles showed a maximum rooting depth greater than the depth to the cap (i.e. rooting into the cap is occurring). In the other profiles, roots have either stopped at the cap or have yet to reach that far.

The potential impact of larger numbers of roots coming into contact with the soil/cap interface and the cap material in 2002 was explored. Approximately 50% of all roots (across all species) approaching within 3 cm of the soil/cap interface penetrated into the cap. These data, relating to just 23 trees of the study, were analysed by a general linear model with logit link function and binomial error term. There is some evidence that species roots differ in their ability to penetrate the soil/cap interface ($p=0.15$) and a larger sample size might have allowed a statistical significant difference to emerge. In contrast, there was no effect of the depth of soil above the soil cap on the likelihood of roots within 3 cm of the capping penetrating it (p=0.47). Table 8 gives the proportion of roots penetrating into the cap between species. Of the roots approaching the soil / cap interface, 72% of sycamore roots, 46% of alder, 46% of ash and just 25% of Corsican pine roots penetrated the cap. Nevertheless, it should be borne in mind that a total of only 38 sycamore roots (6.3% of the total sycamore root count) and nine Corsican pine roots (or 0.4% of the total number of Corsican pine roots) entered into the cap, irrespective of soil thickness. Of the seven trees planted in at least 120 cm of soil, only two had roots that reached the cap and only the roots of one of those trees penetrated the cap.

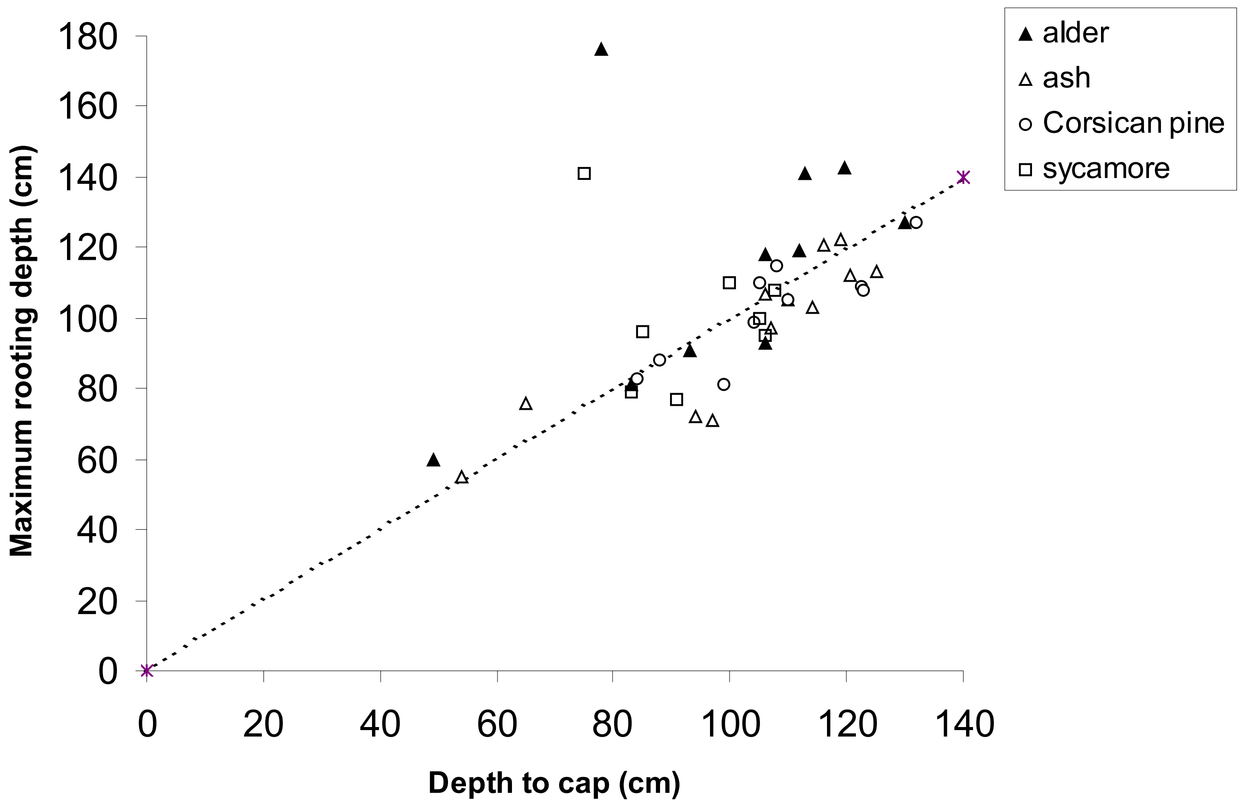


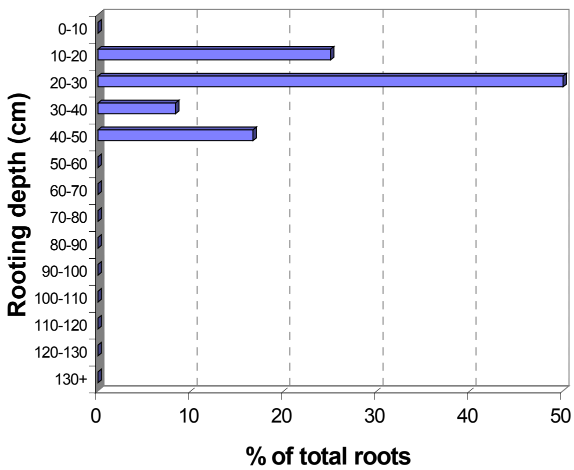
Figure 9: Relationship between cap depth and maximum rooting depth (2002 data)

Species	Proportion of roots (%)	s.e.
Alder	46	0.11
Ash	46	0.12
Corsican pine	25	0.13
Sycamore	72	0.12

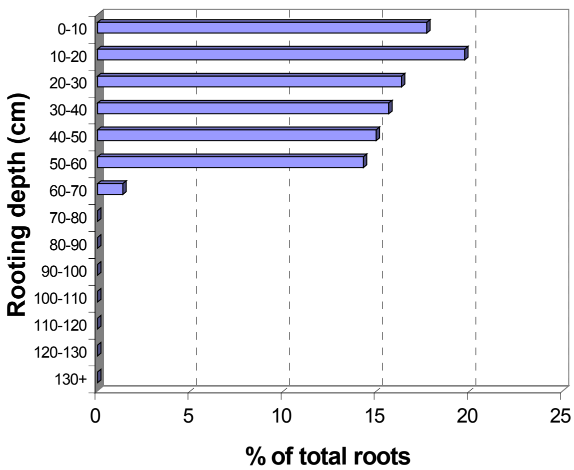
Table 8. Proportion of roots within 3 cm of the soil/cap interface that penetrate the cap. s.e. = standard error

Hutchings *et al*. (2001) found strong correlations between depth to the cap and the rooting depth of individual tree species which were not evident in 2002. The changing relationships between total root count per tree, rooting distribution, maximum rooting depth and soil cover depth between 1997 and 2002 can be explained by the control of rooting depth and root count by species growth habit and morphology in 1997. The trees in the deeper profiles had not encountered any major limitations to rooting imposed by the cap, indicated by the relatively low total root count close to the soil / cap interface in 1997 (Table 7). Since 1997, the trees have begun to encounter limitations to growth and rooting distribution, especially in the shallower soil profiles. In 2002, the depth to the cap imposed a restriction on the maximum rooting depth, the total root count per tree and the distribution of rooting down through the soil cover profile. This may mask any differences in rooting habit (and potential growth rates) between species.

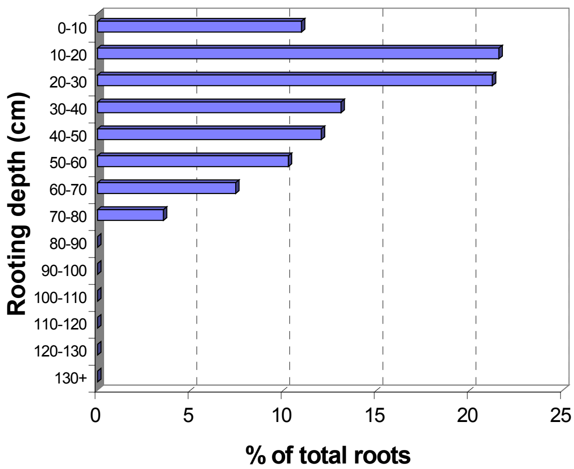
Figure 10 illustrates the effect of cap depth on the distribution of root counts with depth within the profile for 2002 and 1997. The 2002 data show a clear tendency for roots to be heavily concentrated in the upper half metre of the profile where the depth to the cap is very shallow. As the depth to the cap increases, roots become distributed at greater depths within the soil-forming material cover and always appear to exploit the full available soil depth. This contrasts with the 1997 rooting distributions which show that the proportion of roots extending into the deeper soil layers where the depth to cap exceeds 1.1 metres was much smaller and tended to tail off with depth.



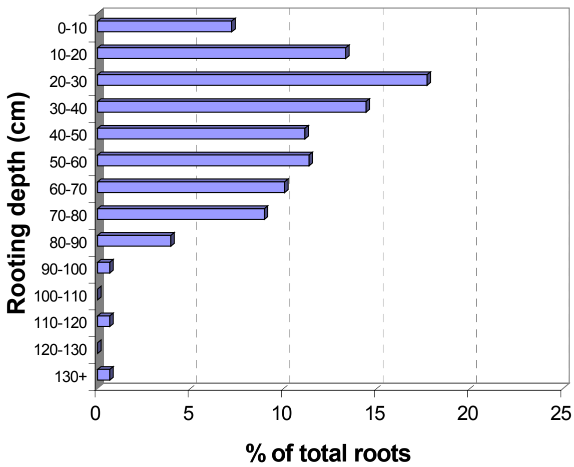
a) Soil depth 49-55 cm over cap 1997
(*note scale)



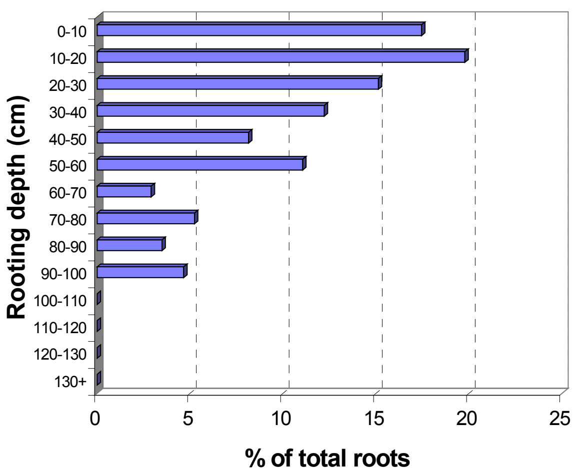
b) Soil depth 49-55 cm over cap 2002



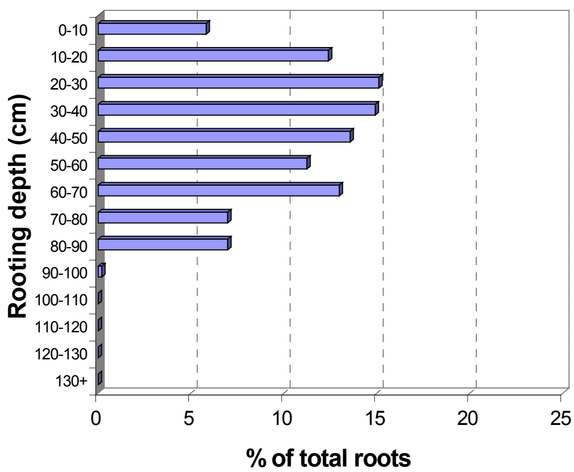
c) Soil depth 55-85 cm over cap 1997



d) Soil depth 55-85 cm over cap 2002

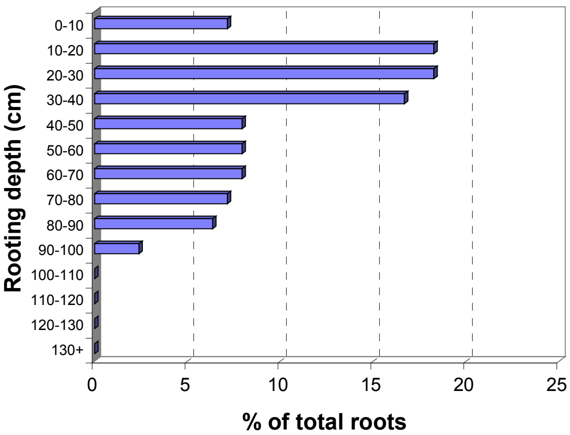


e) Soil depth 85-100 cm over cap 1997

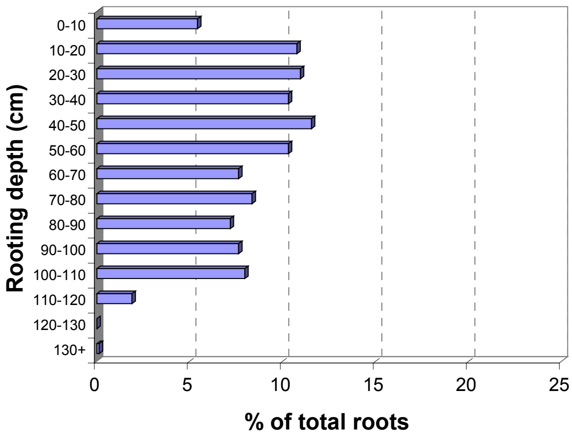


f) Soil depth 85-100 cm over cap 2002

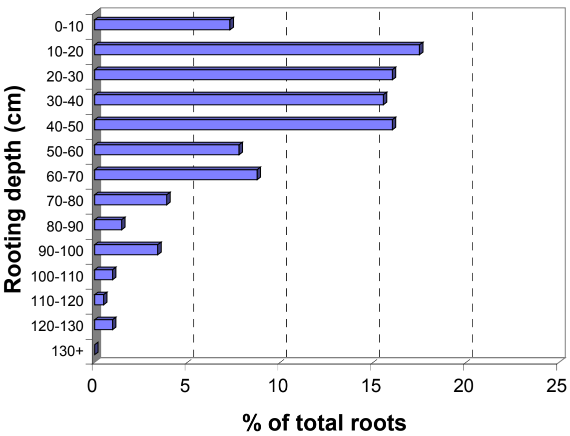
Figure 10a: Rooting distributions in relation to depth of soil over the cap, 1997 and 2002



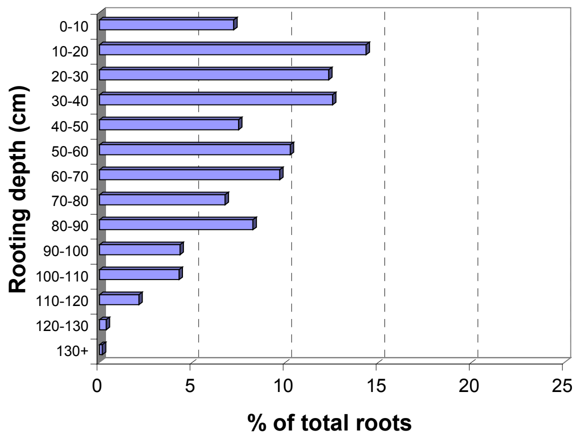
a) Soil depth 100-115 cm over cap 1997



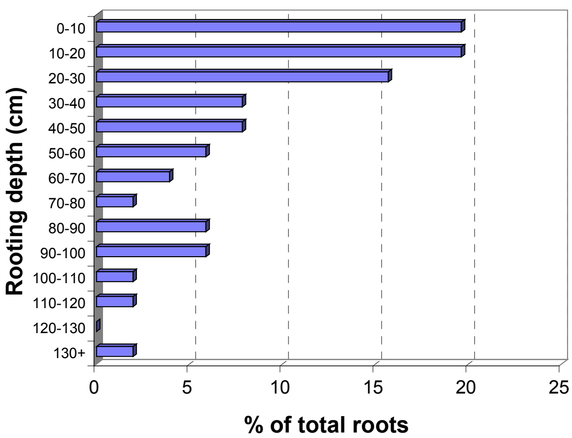
b) Soil depth 100-115 cm over cap 2002



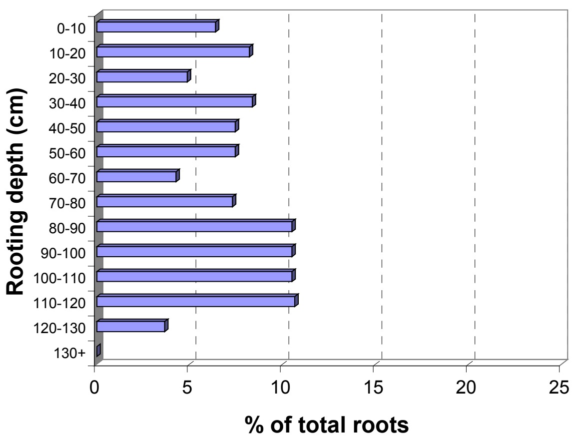
c) Soil depth 115-130 cm over cap 1997



d) Soil depth 115-130 cm over cap 2002



e) Soil depth >130 cm over cap 1997



f) Soil depth >130 cm over cap 2002

Figure 10b: Rooting distribution in relation to depth of soil over the cap, 1997 and 2002

Figure 11 presents scatter plots of the effective depth of rooting into the cap (measured vertically downwards from the soil / cap interface) in relation to the depth of the cap below the soil surface for each of the species. The number of data points illustrated in each plot is equal to the total number of roots of each species which entered into the cap. The root density at the cap interface is indicated for each of the species in Table 8. Example illustrations of deep rooting into the landfill cap are given in Plates 2 to 6. Plate 2 illustrates that, while larger roots show deflection at the soil / cap interface, some finer roots will still penetrate deeper into the cap material. The ability of roots to penetrate the cap may also be related to the uniformity of the soil / cap interface which, as in Plate 2, is often irregular and may serve to deflect roots into a vertical orientation.

The greatest depths of root penetration into the cap were encountered in alder (one root reached 98 cm below the soil / cap interface, Plate 3) and sycamore (66 cm, Plate 5). The depth of penetration into the cap by sycamore roots appears to decline to less than 10 centimetres as the depth to the cap exceeds 1 m. This might be expected, since the nominal vertical extent of rooting of sycamore in freely rooting and well aerated, sandy soils is only up to 1.3 m (Dobson and Moffat, 1993, p.25). However, root penetration depths into the cap of 30 cm were reached at a soil depth of 1.15 m in alder and no evidence of a decline in root penetration depth into the cap with increasing depth of soil cover was evident. These results are commensurate with a ‘typical rooting depth’ for common alder of about 2.0 m (Dobson and Moffat, 1993). Alder and sycamore demonstrated both the highest number of roots reaching the soil / cap interface and the greatest extent of penetration into the cap. The comparatively smaller threat to the cap posed by ash is partly explicable by the tendency of this species to shallower rooting (1.1 m; Dobson and Moffat, 1993) than the others discussed above.

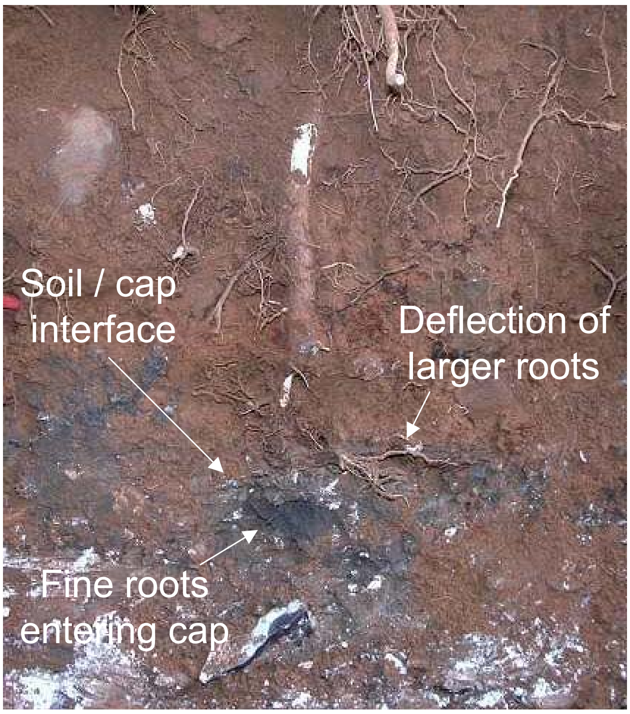


Plate 2: Example of rooting at the soil / cap interface

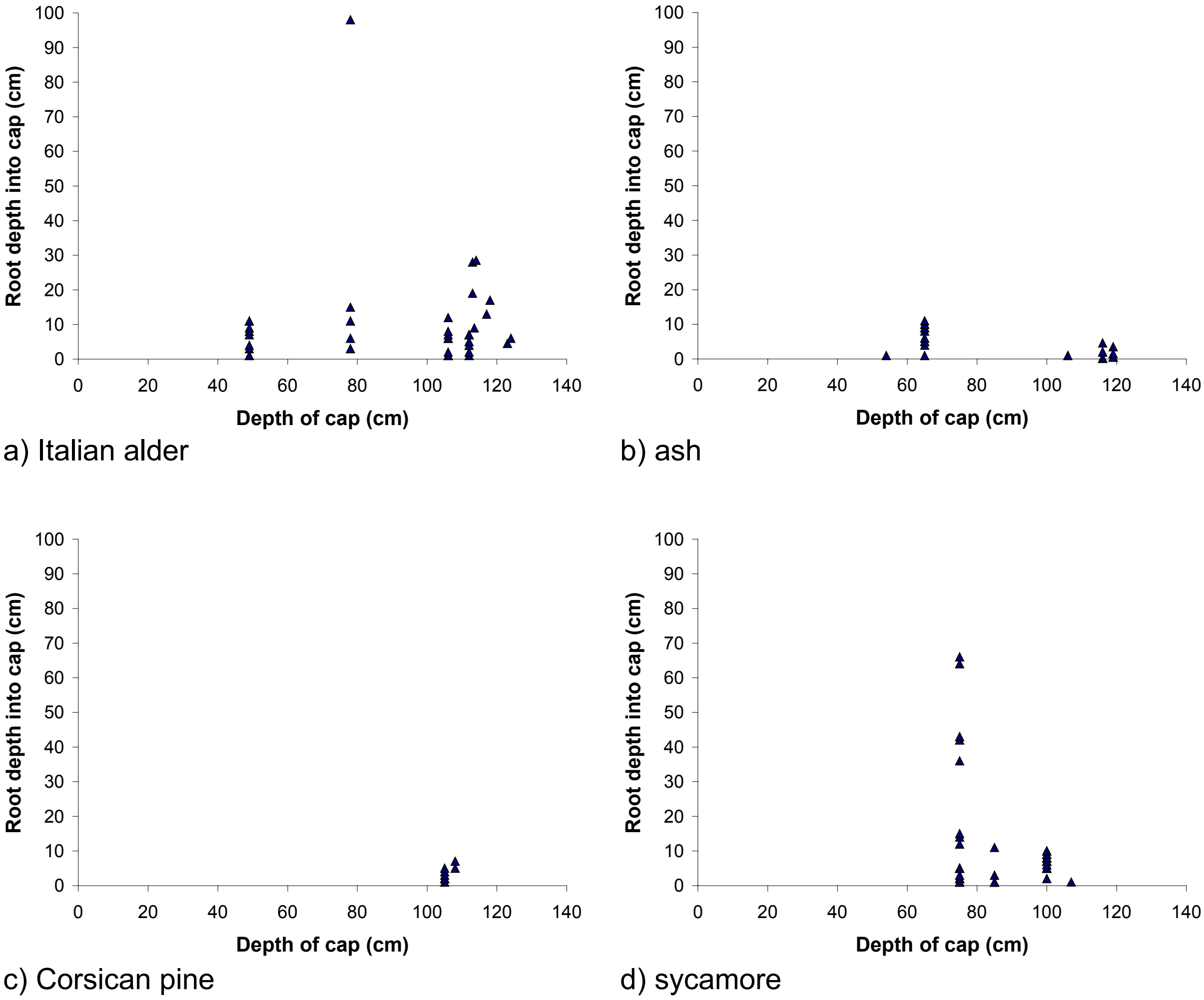


Figure 11: Depth of roots extending into the cap

Figure 12 illustrates differences in the distribution of root diameters and counts between the species. Alder has a high proportion of fine roots which might improve the ability of alder to exploit microfissures or pores within the cap substrate (see also Plate 7 for a close-up photograph of alder rooting within the cap). There was no evidence in the 2002 data of any radial thickening of roots as they approached or penetrated into the cap. This contrasts with the 1997 finding that an increase in radius of between 45 and 60 per cent occurred in the cap when compared to the root radius above the soil/cap interface.

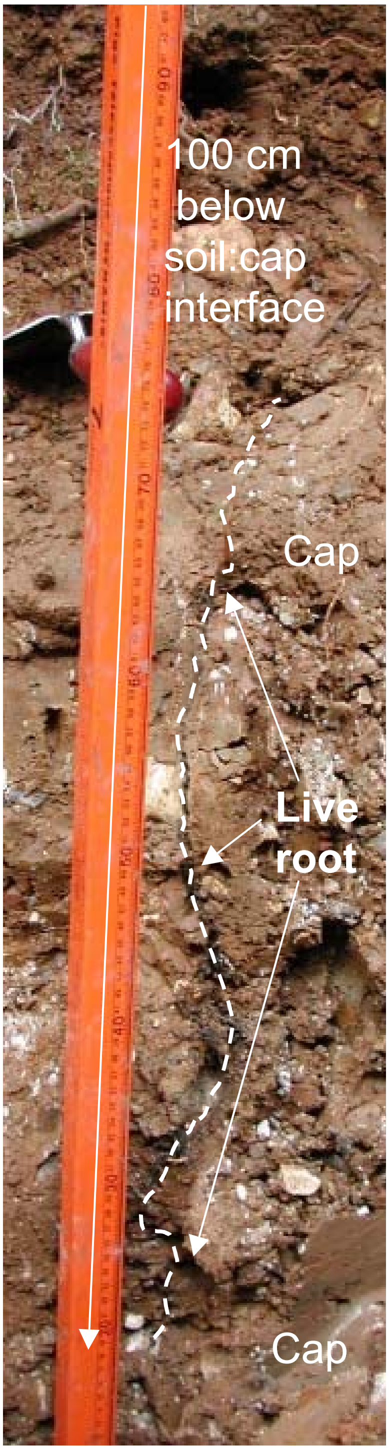


Plate 3: Alder, rooting at 1 metre depth below the soil / cap interface

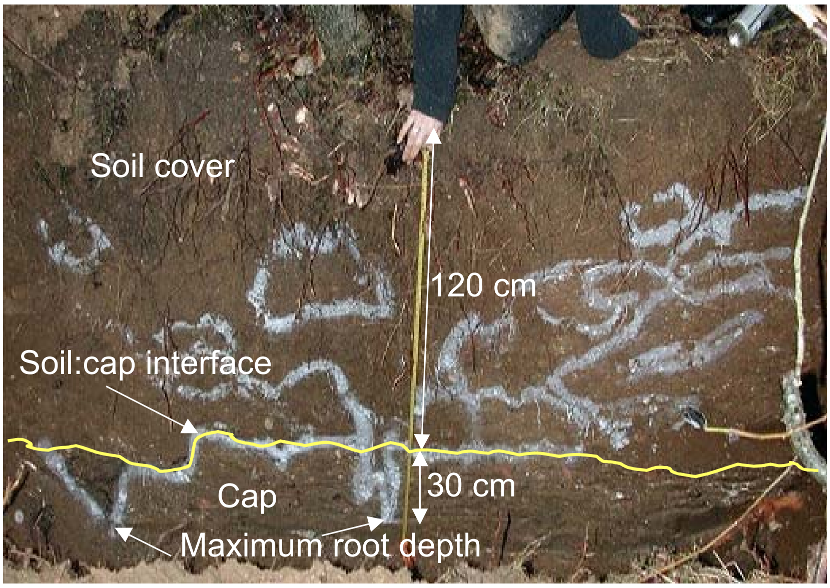


Plate 4: Deep rooting in alder, 0.3 metres below the soil / cap interface

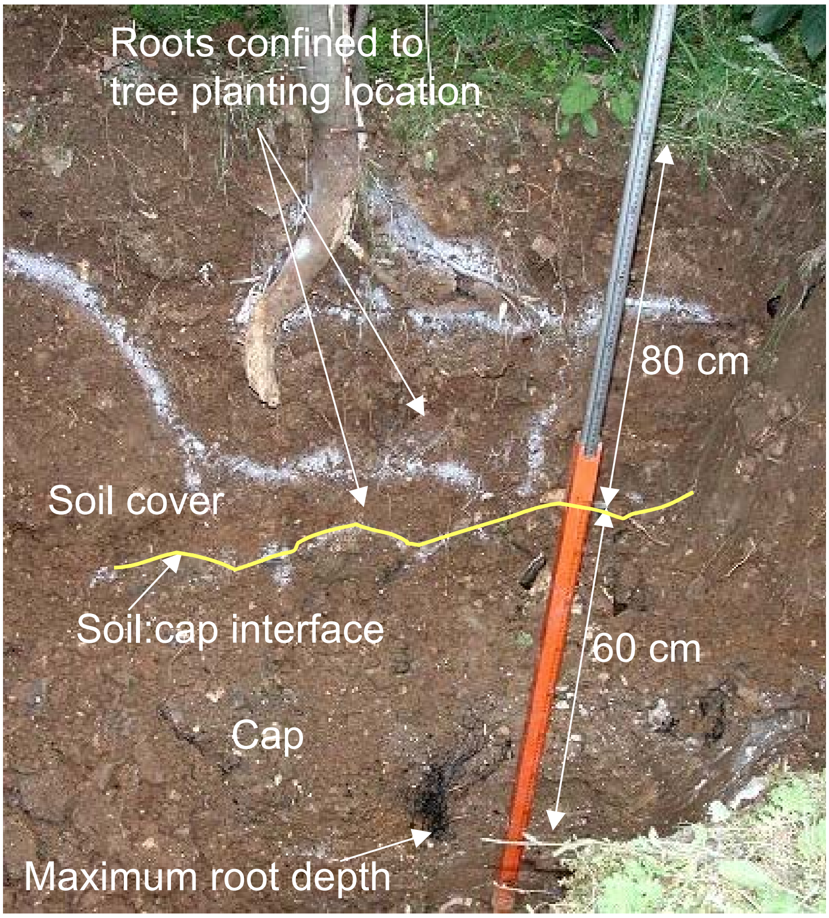


Plate 5: Deep rooting in sycamore, to 0.6 metres below the soil / cap interface

Plate 6: Alder rooting in the landfill cap

(Root locations are denoted by the red pegs. Note the difficulty in assessing the root diameters and locations in the expanded diagram).

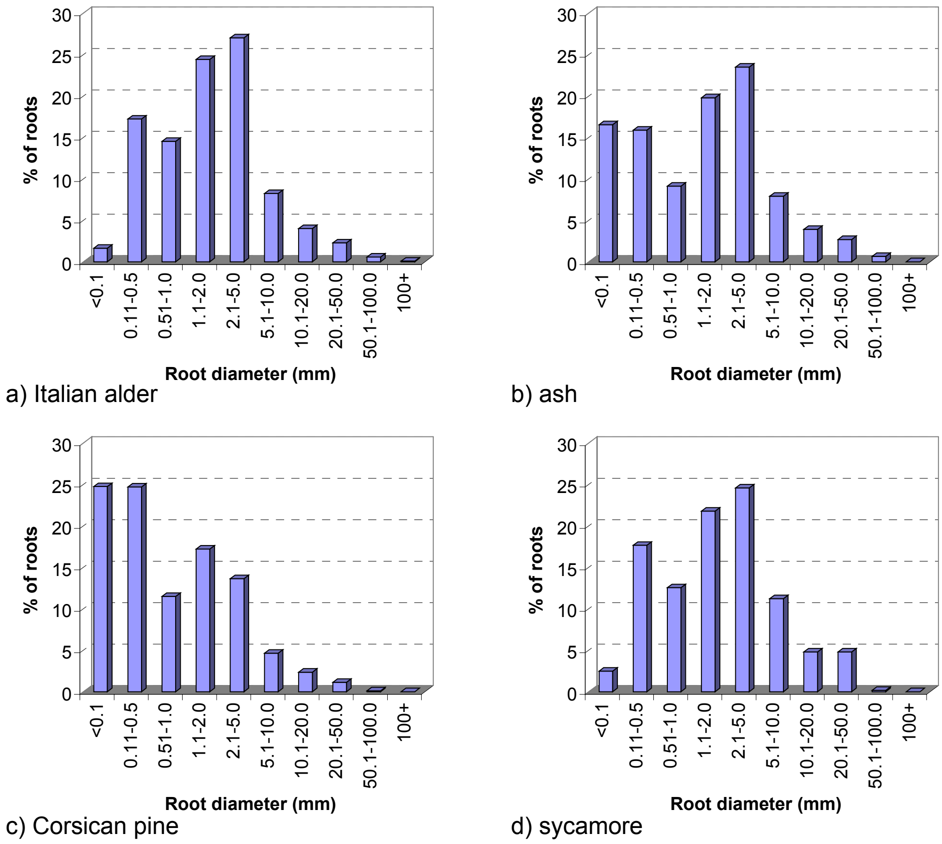


Figure 12: Root diameter distributions for the tree species **(i.e. average roots in soil and cap)**

A generalised linear model with log link and Poisson error distribution was used to model the number of roots entering the cap from the 2002 data (Figure 13). Whilst there was no effect of tree species or total root numbers, an increasing depth of soil above the cap significantly decreased the number of roots penetrating it ($p<0.01$). The model shows that there is an approximately exponential decline in the total number of roots per tree penetrating into the cap as the depth of the soil cover increases. The confidence interval for the model is very large at shallow soil depths, but is much smaller for thicker soil covers over the cap. At a cap depth of 1.25 metres, only one root per tree is predicted on average to penetrate into the cap, and the model suggests that this will rarely be above three roots (95% confidence) These results strongly support the findings by Dobson and Moffat (1993) and Hutchings *et al*. (2001) that the placement of a thick soil cover over the landfill cap will minimise the degree of root penetration into it, and the model supports the earlier contention that a thickness of 1.5 m will reduce the risk of root penetration to almost zero.

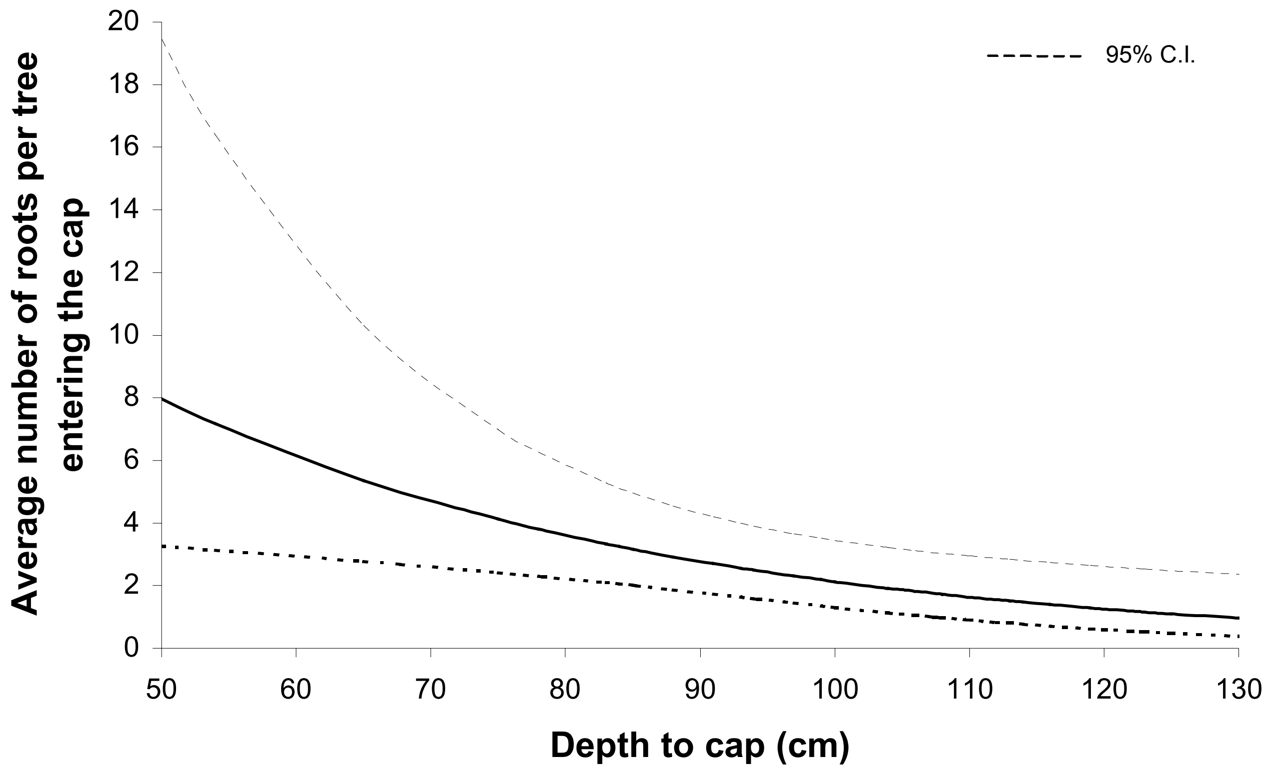
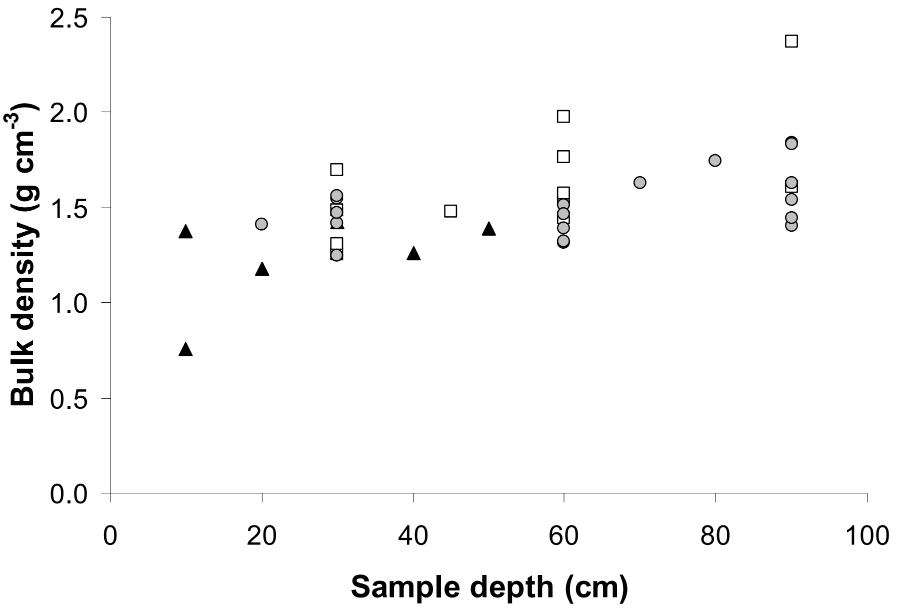


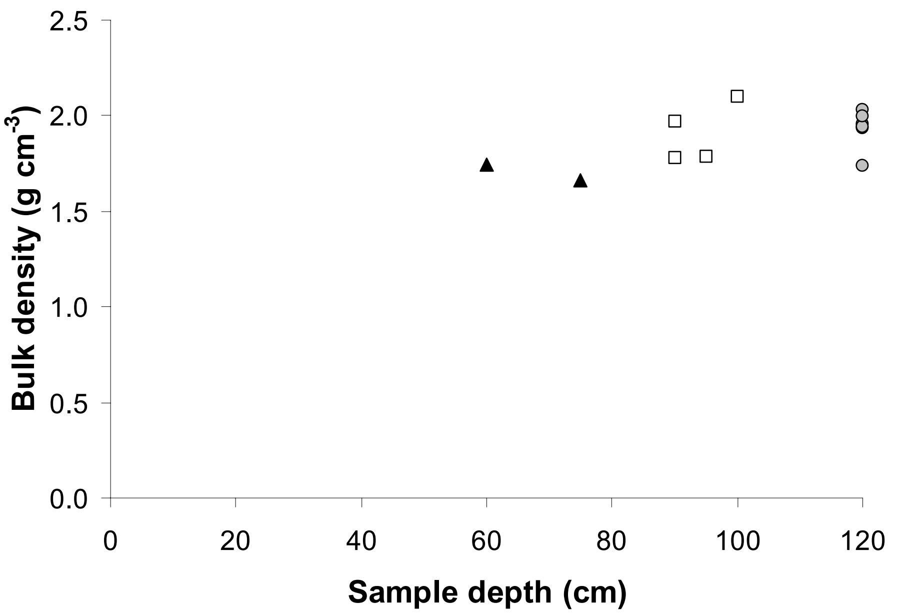
Figure 13: Relationship between the depth to cap and the predicted number of roots entering it. C.I. = confidence interval

3.5.2 Cap composition and micromorphology

One explanation for the extent of rooting into the landfill cap is that the composition of the mineral cap may not be of a sufficiently high standard to prevent root incursion. Figure 14 and 15 presents plots of the 2002 bulk density and soil moisture results with sampling depth for the soil cover and the cap. Table 10 summarises the mean bulk density and soil moisture results for both 1997 and 2002 for different depths of soil cover and cap. Soil bulk density increased with depth as in a typical soil profile in both 1997 and 2002. Almost all soil cover values conformed to the standard requirements 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).

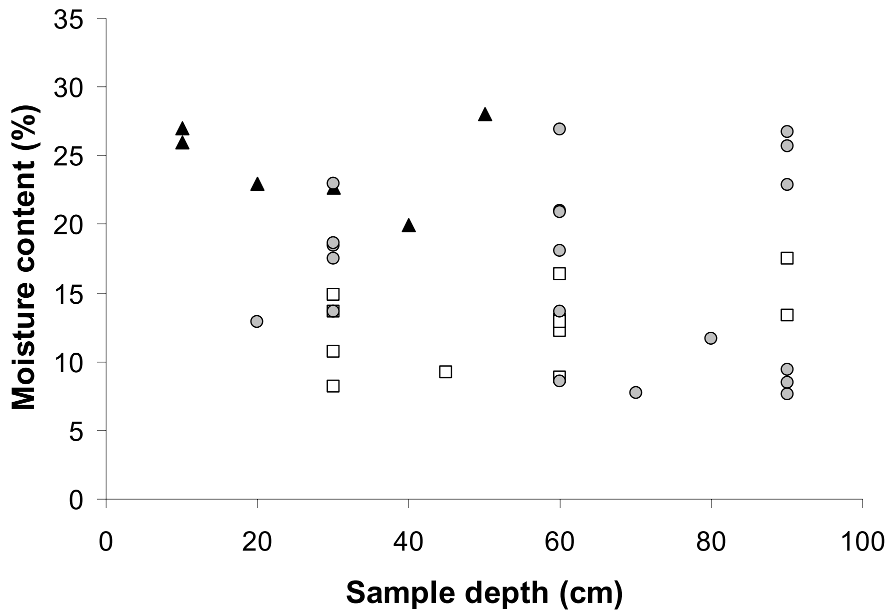


a) Bulk density of soil cover

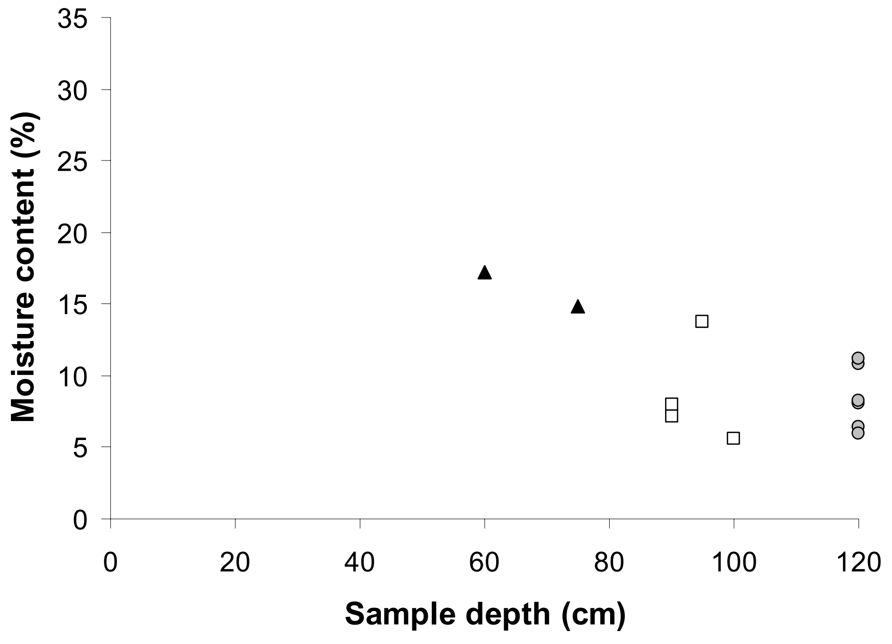


b) Bulk density of cap

Figure 14: Bulk density of the soil cover and cap in 2002



a) Moisture content of soil cover



b) Moisture content of cap

Figure 15: Moisture content of the cap in 2002

Measurements conducted in 1997 showed that the cap had a mean moisture content of 12 % and a mean total dry bulk density of 1.99 g cm^{-3}. The cap material particle size distribution (measured in 1997) was quite variable but was dominantly clay loam with localised 'pockets' of sandy silt loam (Table 9). It also contained a significant component (approximately 20%) of material greater than 2 mm in diameter (Kennedy *et al*., 2000). In 2002, there was a range of cap bulk density measurements from 1.66 to 2.09 g cm^{-3} (Table 10). Few of the samples exceeded the recommended value of 1.8 g cm^{-3} for cap construction (Department of the Environment, 1986, 1995). Cap density samples in 1997 were taken from the base of very deep pits under the deepest soil cover. Collection of cap samples from both deep and shallow profiles in 2002 indicated, however, that the cap bulk density in the shallower pits tended to be lower than the recommended value. It is possible that some heave or loosening of the cap may have occurred in locations where the soil cover was shallow and rooting penetrated into the cap, or as a result of weathering through wetting and drying cycles over 16 years. The lower values may also have resulted from settlement of the cap over time as the landfill constituents decompose, although this would probably be localised in occurrence.

Table 9: Particle size distribution of landfill cap material (n=9)

	% Clay	% Silt	% Silt	% Sand	%Sand	%Sand	% Sand	% Sand	% Stones
	< 2µm	2-20µm	20-50µm	50-100µm	100-250µm	250-500µm	500-1000µm	1000-2000µm	>2000µm
Minimum	9.2	16.5	0.9	1.1	5.7	6.9	4.3	3.3	19.4
Maximum	25.0	41.8	8.8	1.5	8.5	11.4	7.0	4.8	27.3
Mean	17.8	29.2	4.6	1.3	7.1	9.0	5.5	4.0	21.5
Standard Deviation	6.4	11.9	3.0	0.2	1.0	1.6	1.0	0.6	3.3

Table 10: Soil-forming material and cap physical properties

Year	Material	Depth	No. of samples	Mean dry bulk density (g cm^{-3})		Mean moisture content (%)	
1997	Soil Cover	5	4	1.26	(0.18)	18	(3.4)
		25	4	1.38	(0.13)	20	(3.9)
		50	4	1.43	(0.10)	19	(6.6)
		75	4	1.49	(0.12)	16	(6.6)
		100	4	1.53	(0.09)	16	(3.8)
2002	Soil Cover	15	4	1.18	(0.30)	22	(6.4)
		30	11	1.42	(0.15)	16	(4.7)
		60	14	1.51	(0.19)	16	(6.7)
		90	9	1.71	(0.29)	16	(7.5)
1997	Cap	120	4	1.99	(0.18)	12	(6.6)
2002	Cap	60	1	1.75	(0.00)	17	(0.0)
		90	3	1.84	(0.11)	10	(3.6)
		120	6	1.93	(0.10)	8	(2.2)

( ) indicate standard deviation from mean.

Landfill cap porosity was identified from the analysis of thin sections (conducted by Mooney, 2004; refer to Annex 2 for the full report on thin section analysis). The total porosity and mean pore size results are presented in Table 11. The total porosity (measured at the macro scale) varied between 4.3 and 9.5%.

Mooney considered that the higher values are representative of a material with a bulk density in the region of 1.5 to 1.6 g cm^{-3}, supporting the direct measurements of bulk density which suggest that in places the cap does not meet the 1.8 g cm^{-3} standard sufficient to prevent root incursion.

Table 11: Porosity from macro analysis of thin sections **(after Mooney, 2004)**

Scale of analysis	Sample	Description	Total Porosity (%)	Pore number	Mean pore size (mm^2)	No of pores > 5 mm^2
	6	Just above cap, 100 cm, rooted	4.3	297	0.70	11
	7	Soil:cap interface, 53 cm, rooted	8.5	1230	0.22	15
	8a	Top of Cap, 105 cm, rooted	7.9	3680	0.22	26
	8b	Top of Cap, 105 cm, rooted	7.4	809	0.35	28
	11	Top of Cap, 153 cm, rooted	9.5	1318	0.30	17
	4	Cap, 107 cm, unrooted	8.1	1802	0.21	13
	9	Cap, 163 cm, unrooted	5.2	315	0.57	17

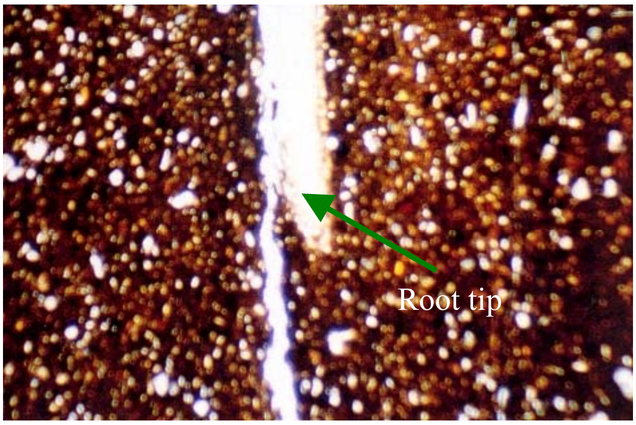
Pores formed shapes (Table 12) predominantly associated with cracking (see Plate 7 d and e) rather than the more rounded pore shapes associated with more friable soils. The pores also had a fairly smooth surface (Table 12) which is typically associated with dense or fine clay matrix material, as opposed to rougher pores associated with coarser grained or sandy material. These pore shape and roughness classes are therefore indicative of soils with a reasonably high clay content. The roughest pore edges were found in sample 7 (at the soil : cap interface) and the smoothest edges in sample 4 (within the cap). The mean pore sizes identified are also relatively large (0.2 - 0.6 mm^2), suggesting a potential for incursion by tree roots. To avoid assisting root penetration one might aim for a mean macropore size of < 0.1 mm^2. Between 70-85 % of the porosity was greater than 1 mm^2, although care must be taken in evaluating these data as one large pore space can significantly skew the distribution (as occurred in sample 8a, see Annex 2). It is also important to note that some of the voids measured may reflect cracking of the samples during their collection from the field or impregnation with resin, significant difficulties having been encountered in performing both of these operations due the stony and compact nature of the cap material. This may partly explain the discrepancy between the measured bulk density results and the micromorphological interpretation of density.

Table 12: Pore shape from macro and micro analysis of thin sections **(Mooney, 2004)**

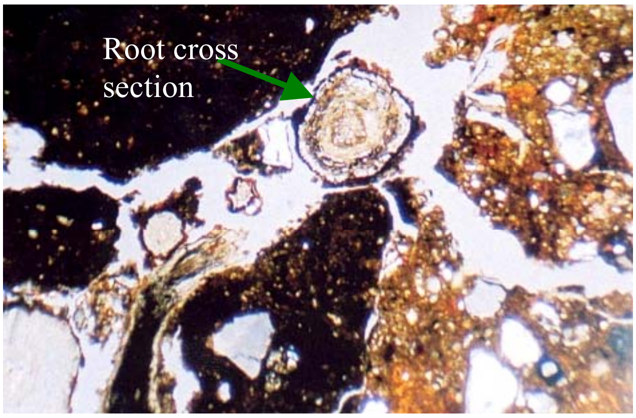
Scale of analysis	Sample	Description	Sphericity (% pores)			Roughness (% pores)		
			> 0.5 rounded	0.49-0.3 irregular	< 0.29 cracked	> 0.5 smooth	0.49-0.3 roughened	< 0.29 very rough
Macro	6	Just above cap, 100 cm, rooted	18	29	54	67	23	10
	7	Soil:cap interface, 53 cm, rooted	17	26	57	47	31	22
	8a	Top of Cap, 105 cm, rooted	20	30	50	59	27	14
	8b	Top of Cap, 105 cm, rooted	19	28	53	50	34	15
	11	Top of Cap, 153 cm, rooted	22	30	48	54	31	15
	4	Cap, 107 cm, unrooted	20	34	46	83	12	5
	9	Cap, 163 cm, unrooted	15	30	55	54	28	18
Micro	4	Cap, 107 cm, unrooted	31	30	39	57	26	16
	6	Just above cap, 100 cm, rooted	42	32	25	82	15	2
	7	Soil:cap interface, 53 cm, rooted	16	29	55	83	12	4
	8a	Top of Cap, 105 cm, rooted	27	26	47	70	22	8
	8b	Top of Cap, 105 cm, rooted	21	27	52	70	22	8
	9	Cap, 163 cm, unrooted	11	30	59	63	24	13
	11	Top of Cap, 153 cm, rooted	15	32	53	66	20	14

Plate 7 presents some selected images taken from the micromorphological analysis, which show the presence of roots in cracks forming alongside stones or at the boundaries between coarse and fine-grained material, as opposed to unrooted sections (Plate 7 c) in more dense fine clay matrix material. The cap was predominantly formed of a mixture of material including both fine and coarse grains, as indicated in Plate 7 e.

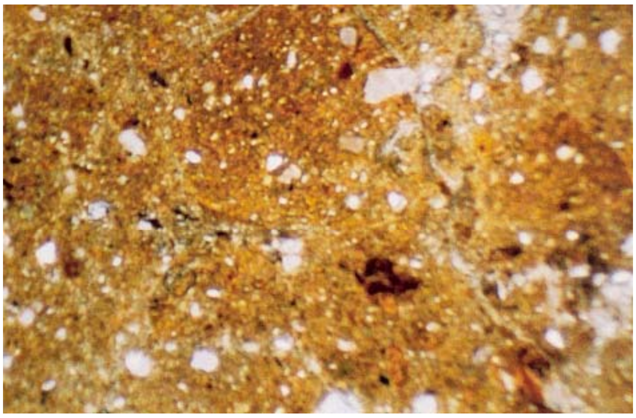
Figure 16 and Figure 17 illustrate the pore distribution within the samples when examined at macro and micro scales. The high degree of variability in pore number indicates significant heterogeneity within the cap material. Considering samples 8a and 8b were prepared from the same thin section, there was a significant difference in total number of pores, mean pore size and pore distribution.



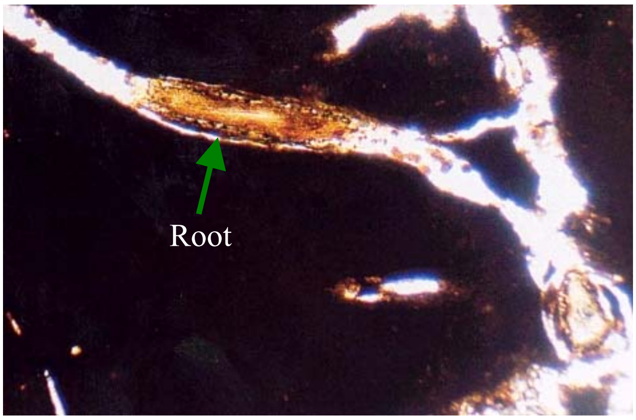
a) Vertical root tip in soil cover



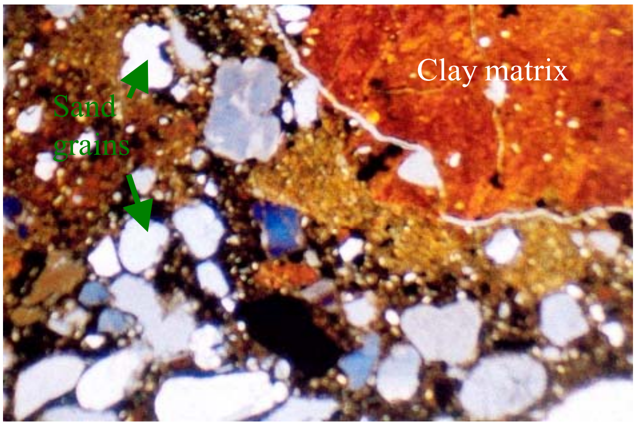
b) Rooting at SFM / cap interface



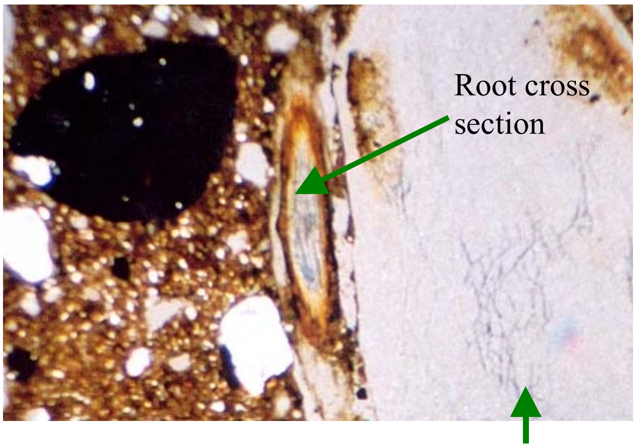
c) Dense, unrooted clay cap matrix



d) Rooting in cracks within cap



e) Example of clay matrix alongside coarse sandy matrix and crack development



f) Rooting in fissure alongside stone

Plate 7: Photographic images from micro-scale micromorphological analysis

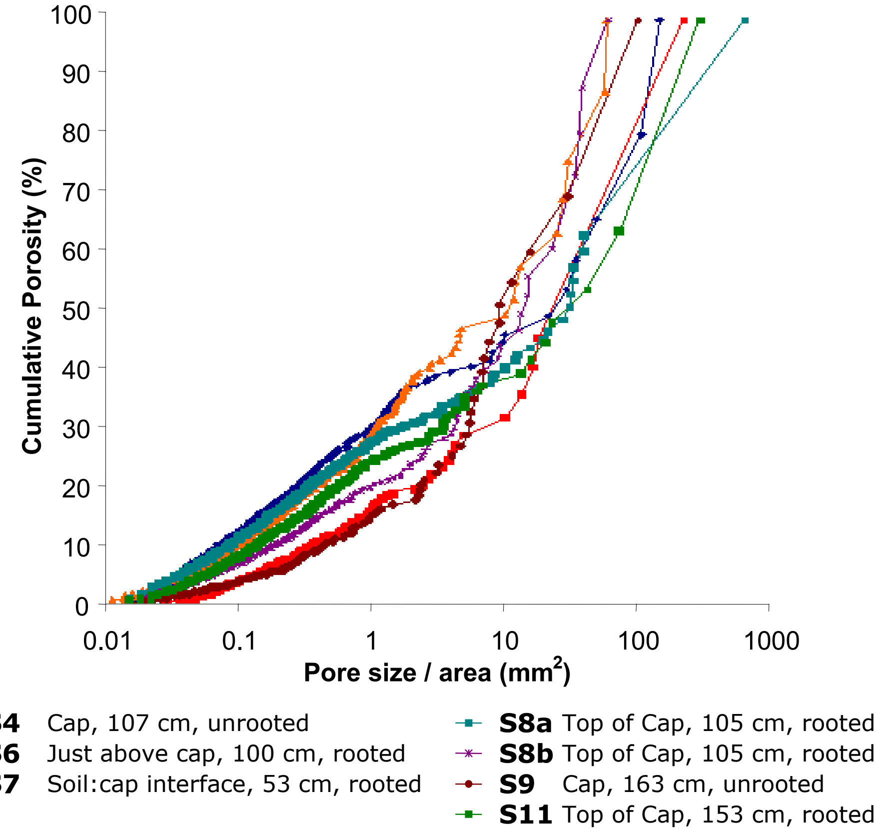


Figure 16: Pore size distribution from macro analysis of thin sections **(Mooney, 2004)**

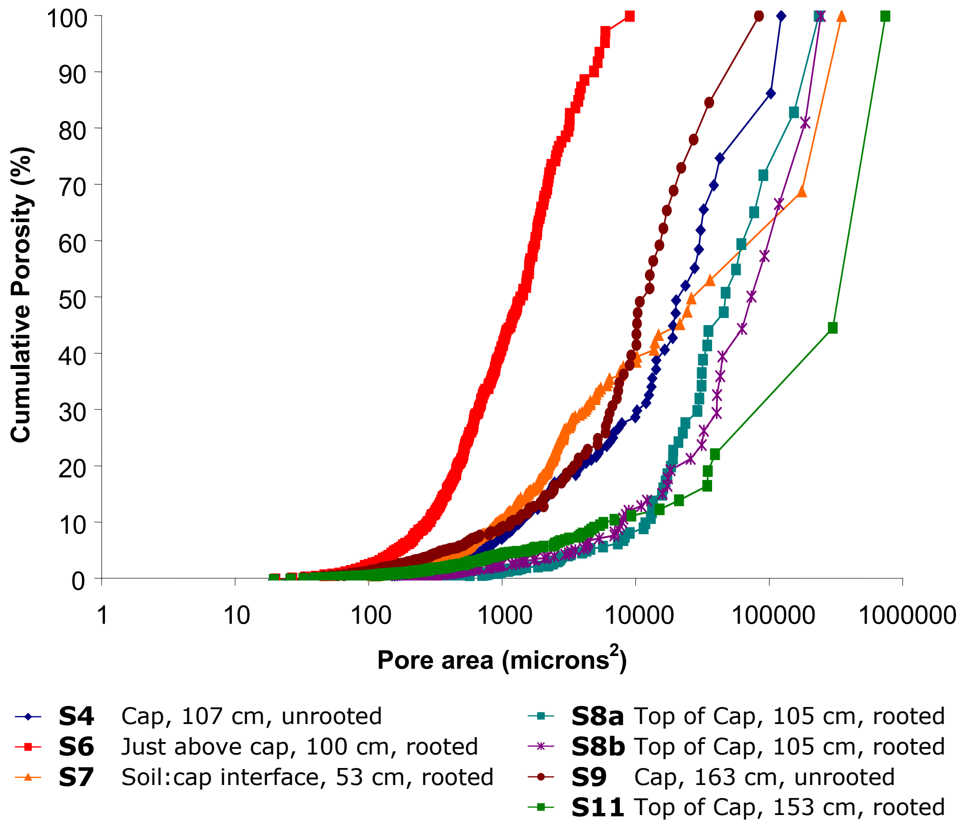


Figure 17: Pore size distribution from micro analysis of thin sections **(Mooney, 2004)**

Micro analysis of pore shape produced slightly different results than the macro-analysis. Sample 6 had a high percentage of rounded pores, which is a reflection of the homogeneous fine sand and silt matrix of the soil-forming material (Mooney, 2004). The dominant pores in the remaining samples were cracked in shape, relatively smooth, and typically accounted for about 50% of the total porosity (Table 12).

The micro-scale image analysis illustrated that the cap material is a highly porous environment that is likely to assist root penetration through the size, shape and arrangement of pores. Figure 16 shows that porosity of the most samples is relatively high. The mean pore sizes of 5733 and 8018 μm^2, recorded in samples 8a and 8b, respectively, are very large and not representative of a compacted porous environment. Only sample 6 had a pore distribution (and lowest recorded mean pore size of 544 μm^2) which might be less conducive to root penetration, and even this sample showed some evidence of rooting. The porosity of the cap compared to the soil cover is clearly demonstrated in the pore distribution of sample 7, taken at the soil: cap interface, where a bimodal distribution of smaller and larger pores was clearly visible. Thin section analysis revealed that this bias related to larger pores identified in the clay cap, compared with the soil cover.

The conclusions from the micromorphological study were:

1. The cap material is predominantly composed of mid-sized quartz grains with a clay mixture (often appearing as isolated pockets or occasionally within the coarse material matrix) and with a considerable stone content. The clay cap fabric appears to be a random mixture of large mineral grains, isolated clay pockets and organic matter fragments.
2. The cap material exhibited a high degree of heterogeneity in porosity and particle size.
3. Sample densities of approximately 1.5 to 1.6 g cm^{-3} were suggested in some thin sections in 2002. These fail to meet the 1.8 g cm^{-3} threshold for modern compact non-porous clay caps.
4. There was evidence of root penetration in most thin sections, predominantly along cracking pores. Rooting was observed to extend in both the horizontal and vertical planes, depending upon the relative positioning of dense matrix material and upon the orientation of cracks or pores.
5. There was significant evidence to suggest that the vertical cracking pores (a result of the clay content in the material) could assist penetration of roots. Roots penetrated vertically into the cap, although at the immediate interface, horizontal or skewed penetration was more likely.
6. There was also evidence that the high stone content within the material formed zones of weakness that the roots can exploit to push through the material in the gaps adjacent to them.
7. Remnant organic material was present throughout the cap profile which may desiccate during drying, causing pores to widen which could also assist root penetration. Most of this organic matter was not from recent rooting activity but appeared to be highly decomposed, depositional material.
8. Little root penetration occurred in areas of high clay content where there was insignificant mineral mixture or cracking by desiccation, suggesting that an optimal density threshold and arrangement of pores can potentially be reached which would prevent root incursion.

9. The soil / cap interface appeared to be at a greater density than the deeper cap material, seen in samples 8-11. Here, there was evidence that roots were deflected from entering the cap to an extent. This may derive from trafficking over the surface of the cap during the placement of soil cover. While there was a structural discontinuity at the interface, however, the presence of many vertical cracking pores would be likely to aid, rather than resist penetration. This interface zone is a critical area with respect to preventing root penetration.
10. Roots exploited weaknesses in the soil fabric at the interface between a stone and the soil matrix but there was no evidence to suggest that these weaknesses occurred within the denser clay matrix.
11. There was a general bias towards the smaller diameter root material with only limited evidence of root diameters greater than 80μm at depth. The largest root diameter identified was 1.1 mm.
12. Few morphological differences were identified between roots of different tree species. The alder roots identified in samples 9 and 11 appeared to have largest root tips and diameters, with the Corsican pine roots in sample 8 tending to be the smallest.
13. Roots typically grow thicker in hard soils (Kirby and Bengough, 2002) but there was no evidence to suggest greater than normal root thickness in any of the 2002 thin sections.
14. Not all cracks contained roots. The inference is that root extension may be dependent upon the continuity of pores, or the presence of a less dense matrix lying between pores which is capable of being deformed or exploited by the root.
15. Evidence of cap shrinkage and weathering processes were present, in the form of extended cracks, fractures and abundant sesquioxide, organic matter and clay deposition features suggesting leaching processes. Pores may crack further on drying to create and extend pore channels.
16. The percentage of clay within the cap was surprisingly low. Where clay pockets were identified within the thin sections (unless they had significantly cracked), they appeared to be areas that roots had difficulty in penetrating.

These factors may explain why root incursion into the cap material at Waterford has occurred to the extent observed. In particular, it appears that the high mineral content (sand grains exceeding 5 mm diameter) has prevented the cap from being compacted mechanically to a density sufficient to retard root penetration.

The samples examined were taken from known areas of root activity, in order to try and identify factors affecting the degree or nature of the root penetration. These samples may therefore not be truly representative of the bulk matrix and it is important to state that, at the time of survey, approximately only 1% of observed roots had entered the cap.

The results of the micromorphological analysis indicate that the following key issues need to be addressed in the formation and composition of the cap materials:

1. Attention should be paid to methods of selecting and manipulating geological clay materials in the field in order to attain the fine matrix, high density and low porosity condition that prevents root penetration. The aim should be to achieve a homogeneous material of high clay content.

2. Reduced stone and sand grain contents would enable a greater degree of compaction to be achieved and would reduce the incidence of fissure development along the margins of the grains.
3. The clay content of the cap should be higher than that studied at Waterford (approximately 30-40%).

4. Uniform mechanical compaction, especially at the upper surface of the cap, is required in order to prevent root incursion. This was evident in some locations at Waterford; for example, root penetration into the cap did not occur in all of the profiles with the shallowest soil cover depth.
5. It would be beneficial to ensure that a thin layer of dense clay matrix or an appropriate artificial liner is present at the soil / cap interface, to increase the effectiveness of the barrier against roots.
6. There is evidence from micromorphological work at Waterford to support the studies recommending a minimum bulk density threshold of 1.8 g cm^{-3} in order to prevent root incursion; however, the extent to which this is actually attained using materials of differing geological origin and different compaction methods should be verified using suitable (for example micromorphological) methods, prior to and during cap installation.
7. Further examination of restoration procedures appears to be required, in order to ensure that the required level of compaction is produced during the cap installation.

Adopting these suggestions and improvements to the clay cap material selected, and further evaluation of the restoration procedure, would help to ensure that the clay cap is a more suitable barrier and is placed in appropriate ways to prevent root incursion.

3.6 SUMMARY

The results of the Waterford investigation show that:

1. Trees at age 16 are starting to encounter restrictions to growth and rooting as a result of inadequate soil cover depth and position on ridge.
2. The total number of roots increased significantly since the 1997 study and the pressure of rooting on the cap has increased, but only 2.5% of the total root count penetrated into the cap.
3. There was a strong and significant relationship between the thickness of the soil cover and the number of roots per tree entering the cap. Less than 1% of roots are predicted to enter the cap where the depth to the cap is greater than 1.25 metres.
4. Approximately 50% of the total root count approaching the soil / cap interface succeeded in penetrating into the cap, and cap penetration was more common in shallow soil covers.
5. Alder and sycamore appeared to be the most vigorously rooting of the species and produced the greatest degree of incursion into the cap.
6. The cap at Waterford was not uniform in nature and root incursion had occurred in locations where the matrix was relatively loose, fissured and in proximity to sand grains or stones. However, pockets of unrooted and denser, high clay content material within the soil cover and cap fabric give clear indications that rooting can be inhibited provided that the cap material is of a sufficiently compacted and uniform standard.

4. GENERAL DISCUSSION

4.1. Factors affecting tree growth on landfill sites

There is clear evidence to support the hypothesis that a soil cover in excess of 1 metre depth is required in order to sustain a reasonable tree growth rate over the first ten years. The depth of soil cover appears to play a critical role in providing available moisture and nutrients but also in buffering the clay cap from potential root incursions. The statistical model developed from the Waterford 2002 data suggests that 1.5 metres of soil cover is required to reduce the likelihood of root incursion into the cap to levels of below 1.5% of total tree roots.

At Waterford, the majority of roots appeared to concentrate in the upper 50 to 60 centimetres in the profile, but the rooting habit or vigour of different species also plays a role in determining the root distribution pattern. The pattern of root distribution within the profile and the relationship of roots with the cap may also reflect other factors such as the degree of compaction within different layers in the soil cover material or the relative availability of moisture or nutrition. For example, in Plate 8, a simple classification of rooting distributions in relation to soil structural conditions (using the Foot (2000) method) showed that roots concentrated into "pockets" of looser soil-forming material. Zones of dense compact material were encountered which deflected and constrained rooting in a horizontal and also a vertical direction, preventing them from reaching the soil : cap interface.

The mechanisms by which roots extend and grow through soil and in hard or compacted ground have been relatively well explored in the scientific literature in recent years. As a root enters a soil it must first either exploit an existing fissure or deform the soil to initiate a cavity and then enlarge that cavity to accommodate further growth. Roots grow by a process of cell division just behind the tip of the root and through cell expansion in a zone just behind the apex of the root (Clark *et al*., 2003). Water influx into cells generates a turgor pressure which provides the driving force for cell expansion and elongation. Roots compress the soil cylindrically (Greacen *et al*., 1968) by radial expansion behind the tip in order to expand pores which are smaller in dimension than the root and by exerting axial pressure to displace soil particles at the root tip. The combined expansion and growth pressure and drying induced by the root tip may also open up tensile cracks in front of the root tip and allow further root penetration.

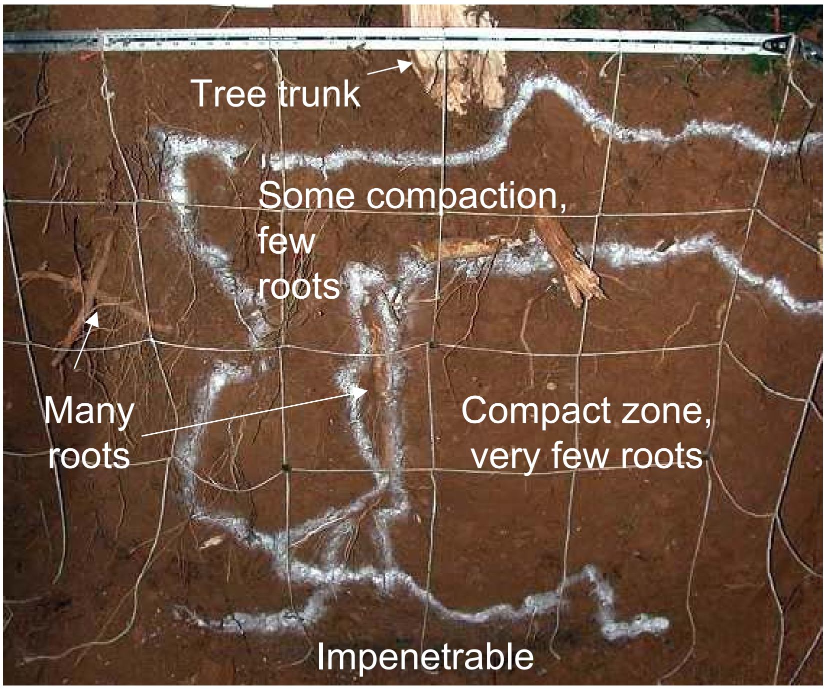


Plate 8: An example of ash rooting distribution within the soil cover

In this way a root may take advantage of existing planes of weakness in the soil. Drying of water filled pores by roots also increases localised shrinkage of clays, causing pore expansion and cracking ahead of the root (Dexter, 1991). However, water uptake may also increase the soil strength and impede further root extension in non-shrinking soils or those with a high confining pressure, as in a dense clay cap. The resistance to root growth through aggregates or clods of soil increases with increasing soil strength (Young and Bengough, 1989), partly due to the increased force required to displace soil particles (Clark *et al*., 2003). Research also shows that the production of root hairs to anchor a root (Stolzy and Barley, 1968) and the stress history of a species (Clark *et al.*, 2003) can affect the ability to penetrate into strong soils.

The physiological mechanisms by which tree growth rate responds to changes in rooting conditions or as a result of moisture or nutrient stress are less well understood. Research suggests that strong soils have the ability to limit both root and shoot growth (Masle and Passioura, 1987; Montagu *et al*., 2001) but no known studies specific to tree root and shoot responses in strong or compacted soils are known. The biomass of fine roots is usually much larger in soils that are infertile or which suffer from drought (Persson, 1983; Fitter, 1999) and this has been attributed to the need to exploit a wider soil volume in order to obtain moisture and nutrients. Moisture availability and drought also affect root-shoot development, with increasing above-ground biomass observed as fine root production increases in some hardwood species (e.g. Scots pine; Vanninen and Makela, 1999). However, root system development appears to be the driver in defining above-ground biomass production and is affected more by ground conditions than by species type or growth habit (Bertson *et al*., 1997).

Root growth, and hence tree survival and growth, will only be sustainable where the basic conditions for plant survival are met. The key to successful management of trees on landfill sites is to promote good conditions for growth in a deep overlying soil cover and to engineer the underlying cap to a standard sufficient to completely inhibit roots. The aim is to provide the tree with the resources of water, oxygen and nutrients that it requires from the overlying soil cover, in order to reduce the likelihood of root incursion into the cap.

4.2 Reclamation requirements for tree establishment on landfill sites

The field-based landfill research strongly suggests that in the soil cover, the following conditions should met:

1. At least 1.5 metres depth of uncompacted soil if placed over an unprotected mineral cap. If possible, an additional 15% depth of soil should be placed in order to allow for soil bulking during placement and resettlement over time. Without a suitable geotextile or bio-barrier, trees should not be planted on a soil cover less than 1.5 m thick. Where a geotextile or synthetic barrier to rooting is present, the results from Waterford suggest that at least 1 metre depth of overlying soil is required to provide conditions to sustain root and shoot growth, and that the soil depth may need to be greater in locations prone to drought (e.g. as at Grunty Fen). In normal circumstances, the ridge and furrow landform, as used at Waterford, will not be required where average slopes exceed about 5 degrees.
2. The soil should be loose, free from compaction and rootable. At least 30% of soil pores should be of diameter 10-100μm to allow root entry but at least 30% of the pores should be of diameter >100μm to allow rapid drainage and air entry (Landon, 1991).
3. Good soil aeration. Roots need a minimum air filled porosity of 10% of the soil volume in order to grow (Wesseling, 1974; Meyer *et al*., 1985).
4. Soil water content. Excess water will cause anaerobism and root death, and compromise tree survival and growth. However, inadequate plant available water will also affect survival and growth. The droughty conditions at the Grunty Fen site in this study had a significant adverse impact on tree survival and growth. Droughty soil materials should be avoided wherever possible, and if used, they should be improved using organic residues to retain moisture. Soils which experience prolonged waterlogging, especially during the growing season, should be avoided if possible. If clayey materials must be used as soils or soil-forming materials, species choice should be restricted to those known to tolerate winter waterlogging, such as alders, willows and poplars. However, there may be a slightly greater risk of mineral cap root penetration if these species are used (Bending and Moffat, 1997).
5.
6. Essential nutrients and pH. Nitrogen, phosphorus, sulphur, potassium and calcium are essential for root development. Soil pH affects the relative availability of nutrients to roots. The foliar results in this study indicate a clear demand for additional nitrogen and phosphorus applications to sustain

tree nutritional requirements, a need which may have been averted by providing a good supply of organic matter or manure during the soil cover instatement.

7. Tree species must be selected to match site conditions. Species must match the acidic or alkaline nature of the soil materials, the level of soil fertility, and the need to tolerate winter wetness and/or summer drought.

From the results and observations at the field experimental sites, there are three key recommendations for the creation of clay caps:

1. Geological clay materials should be selected with care. Preferred materials would show low shrink-swell capability (preferably 1:1 rather than 2:1 lamellar clays), low sand and stone content and very high clay content.
2. The bulk density of the cap should be at least 1.8 g cm^{-3} in order to prevent root incursion. The evidence collected to date at Waterford suggests that this standard set by Waste Management Paper No 26 (Department of the Environment, 1986) remains suitable to prevent root penetration.
3. More care should be given to methods of compacting the clay material to achieve a dense matrix, particularly at the cap surface. The proportion of roots which enter a vertical crack decreases with decreasing crack width and with angle of approach to the direction of the crack (Dexter, 1986a, b). Vertically orientated cracks allow the most rapid penetration of soil by roots (Klepper and Rickman, 1991), so it is critical to increase the compaction level of the upper surface of the cap and reduce the incidence of fissure formation. The evidence from the micromorphological studies of the Waterford landfill cap suggests that vertical crack formation in the upper section of the cap is significant in encouraging roots to penetrate into the material.

The Waterford study supports the presumption that a cap of 1.8 g cm^{-3} would be sufficiently dense to prevent root incursion. However, it suggests that this standard may not be universally achieved or maintained in the field, bearing out findings from other research (Melchior, 1997). It remains unclear to date whether *some* incursion of roots into a cap poses a significant risk of increased pollution or migration of landfill contents.

A clay cap with a dense, uniform and higher clay content matrix is likely to resist root penetration for the following reasons:

1. There would be a high confining pressure to reduce the ability of the root to apply a radial or axial pressure sufficient to displace soil particles or expand pores. The maximum pressure that a root can exert in order to displace soil (the “maximum root growth pressure”) can range from 0.24 MPa for sunflower seedlings (Misra *et al*., 1986) to 1.31 MPa for pea seedlings (Taylor and Ratliff, 1969). Maximum root growth pressures have not been determined for different tree species but the same principle applies.
2. The same high confining pressure would reduce the likelihood of shrink-swell activity during wetting and drying and reduce the rate and extent of micro-crack formation (this will, however, depend upon the clay mineralogy).

3. The continuity of pores of a size sufficient to allow continuous penetration of the root tip down through the cap material would be significantly reduced. The pore size distribution of the cap would be more homogeneous with a bias towards very small pores. The ability of roots to grow into pores smaller than their nominal diameter is limited by the size of the root cap and the extent to which the stele can narrow in response (Scholefield and Hall, 1985).
4. Roots require a pore size distribution which will encourage free movement of oxygen and drainage in order to grow. Materials with an oxygen-filled pore space of less than 3-5% discourage root growth.

The selection of tree species for planting on landfill sites should be conducted with care. The research programme has demonstrated how correctly chosen, some tree species can survive well and thrive on most landfill substrates, but that some species fail almost completely. It seems obvious, but it is worth stating that irrespective of objectives set for a woodland, a large and sustained survival rate should be the driving force behind site restoration, species selection and subsequent aftercare. If tree mortality is large, a woodland will not have been established, and future maintenance will be troublesome and costly.

With respect to protection of the landfill cap, this study has shown that different tree species appear to have different propensities for root production or fine root development and the vigour of rooting. This affects their ability to exploit water and nutrient reserves in the soil cover and is also important in reducing the risk of root incursion into the cap. To protect a mineral cap unprotected by a geomembrane or other form of liner, less vigorously rooting species are to be preferred. It is critical to ensure that species are chosen which are relatively tolerant of both drought and waterlogging. Drought appears to be a very significant factor in determining survival and overall growth performance and it may become more important, given predictions of increasing drought in the UK due to climate change (Hulme *et al*., 2002; Broadmeadow *et al*., 2004).

The recommendations above are strongly in line with early proposals for landfill reclamation (restoration and aftercare phases) by Dobson and Moffat (1993), Bending and Moffat (1997) and Kennedy *et al*., (2000), based on literature review, expert judgement and limited experimentation. However, they are supported now by the detailed research undertaken at the five field experimental sites over a ten year period and at Waterford in 1997 and 2002. Nevertheless, the trees at the Waterford site are only 16 years old, and they show evidence of beginning to experience restrictions to rooting. The pressure of rooting and the impact on cap integrity is expected to develop further as the trees grow and mature and as the rooting system develops.

The five tree species experiments and Waterford site are valuable resources, 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. More reliable information will become available as the monitoring plots mature further.

5. CONCLUSIONS

The ten year research project has demonstrated that good tree performance on modern landfill sites can be achieved in Britain, given the hostile conditions associated with the landfill environment and despite instances of drought which have resulted in slower tree growth rates at some sites. The trees are of a size where weed control and maintenance can be relaxed and changes in growth trends are now more likely to reflect longer-term environmental conditions. Poplar, alder, cherry, whitebeam, oak, ash and Corsican pine seem well suited to the landfill environment, and can be recommended subject to specific site limitations (including likely future climate), provided the underlying mineral cap is constructed to the standard required by government legislation.

Examination of tree rooting distributions in the soil cover and landfill cap at Waterford have identified that the total number of roots produced by individual trees increases sharply as the trees age, but that a soil cover of 1.5 metres is sufficiently deep to prevent more than 98% of all tree roots from reaching the soil / cap interface, for trees of age up to 16 years. However, the micromorphological study showed that the landfill cap is relatively penetrable due to its relatively low bulk density, high porosity and sand grain content. There was also evidence that the cap material may weather and crack as roots penetrate into the matrix. Zones of denser fine clay matrix within the cap fabric appeared to resist root incursion, suggesting that the standards for cap instatement set by Waste Management Paper No 26 (Department of the Environment, 1986) appear to be appropriate.

The Waterford tree growth data indicate that restrictions to growth may be emerging in trees which exceed approximately 6 metres in height where soil resources and/or effective root exploitation are limiting. This site does not meet the requirement for 1.5 metres of soil cover, but it is likely that in droughty areas or in soils with low moisture-holding capacity, a greater soil cover depth will be required to support the moisture demands of mature trees. Drought and nitrogen deficiency are key factors which are capable of limiting tree growth at some of the experimental sites, but the significance of the landfill cap in restricting further growth will require more investigation as the trees mature.

6. FURTHER WORK

The results suggest that it is still a little early to ascertain the full impact of tree rooting on cap integrity or the interaction between conditions within the landfill cap and tree rooting as the trees are not yet fully mature. Further work to continue the tree performance assessment and Waterford studies would provide valuable information about the longer-term prospects for tree growth and rooting within soil covers of depth 0.5 to 1.5 metres overlying a landfill cap. The long-term tree performance plots also offer a resource for future research to investigate root growth and gas migration impacts, the potential for rainfall interception and water migration into landfill and the risks of windthrow in soil covers of restricted depth under woodland.

Key questions that have emerged from the study at Waterford are the degree to which “modern” landfill caps attain a bulk density of 1.8 g cm^{-3} sufficient to completely prevent root incursion and whether a minimal degree of root incursion into the cap is actually of any significance in terms of pollution risk through landfill gas migration or infiltration of water into the landfill. A micromorphological examination of different geological clay materials typically used in the formation of landfill caps may provide a useful insight into the density, porosity and condition of the cap at the time of instatement and the potential for root incursion, which may aid decisions about appropriate planting covers. Further investigations could also examine the degree to which the landfill cap may weather physically and chemically. Different mechanisms for screening and compacting such clay materials in order to ensure they reach the required standards set in Waste Management Paper No 26 are also recommended.

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