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TREE ESTABLISHMENT AND GROWTH AT PITSEA LANDFILL SITE, ESSEX, U.K.*

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Investigations at an 11-year-old landfill site have shown that soil moisture was positively, and soil oxygen was negatively correlated with temperature and concentration of soil methane generated by decomposition of the underlying landfill materials. A thin (0.2 m) cover of soil-forming material over the landfill showed acute oxygen deficiency and high temperatures. The high moisture content of this cover was probably caused by upward movement of water from within the landfill across a temperature gradient. Nearly all the trees of five species on the thinnest (0.2 m) cover died, but survival and growth was markedly improved on 1.5 m additional clay cover over the landfill. This material prevented landfill gas contamination, and also contained sufficient plant-available soil moisture to negate the large soil moisture deficits the area experiences in most summers. The evidence presented shows that landfill sites are dynamic in the distribution of landfill temperature and gas emissions and the planning of tree planting schemes should take this into account.

Key Words—Landfills, reclamation, soil temperature, landfill gas, soil anaerobism, soil water, tree growth, U.K.

1. Introduction

It is well known that landfill sites are hostile places on which to establish a vegetation cover (Leone *et al.* 1979, Flower *et al.* 1981, Gilman *et al.* 1981*b*). All man-made sites can suffer from lack of topsoil, soil compaction, poor drainage or drought, but plants on landfill sites can also be affected by the presence of pernicious leachates and landfill gases (Department of the Environment 1986), and high soil temperatures and soil subsidence (Gilman *et al.* 1985). The presence of landfill gases in the root zone is generally perceived as a major threat to plant life. Gases such as methane and carbon dioxide displace oxygen and cause anaerobism. Other gases such as ethylene (Department of the Environment 1986, Emberton & Parker 1989) can cause root systems to deform (Fitter & Hey 1981). High soil temperatures may also contribute to the difficulty in establishing or maintaining vegetation on a landfill site. Binns & Fourt (1983) suggested that heat generated by anaerobic fermentation within the waste material may dry out the overlying soil and thereby reduce its plant-available water. Root growth will also be inhibited where soil temperatures are greater than optimum (Payne & Gregory 1988).

Soil temperatures above landfill have been studied in America (Gilman *et al.* 1981*ab*, 1985), but in the U.K. little or no information exists on the level and effect on trees of high temperatures in the root zone, or on the length of time such temperatures prevail. Temperature monitoring was therefore begun in 1983 on an experimental area at the Cleanaway Landfill Site, Pitsea, Essex, U.K. (National grid reference TQ 743852); an

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* Based on a report in *Seesoil* (1987), *4*, 66–83

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experiment to investigate the influence of thickness and type of cover material covering domestic landfill on tree establishment had been established there in 1978. Temperature measurements were supplemented by measurements of soil methane and oxygen concentrations, soil moisture content, tree survival and growth in 1986.

2. Site details

The Pitsea landfill site is situated on the north side of the Thames estuary and is approximately 360 ha. It has been used for both industrial and domestic waste for over 50 years. Most of the domestic refuse was brought in by boat which came down the river from Greater London. Refuse is spread in 2 m layers, each covered with 0.2 m soil, to a maximum depth of 7 m.

The experiment at Pitsea was laid out to a randomized design with three replications. It tested tree survival and growth on four thicknesses of additional cover (0.0, 0.5, 1.0, 1.5 m) over a layer of 0.2 m composted refuse on the landfill, which was three years old at the beginning of the experiment in 1978. Two types of cover were tested: composted refuse from an area of landfill between 40 and 75 years old; and weathered London Clay (Eocene) overburden. Sixteen trees of each of five species—Corsican pine (*Pinus nigra* var *maritima* (Ait) Melville), False acacia (*Robinia pseudoacacia* L.), Common alder (*Alnus glutinosa* (L.) Gaertn.), Goat willow (*Salix caprea* L.) and poplar (*Populus trichocarpa* 'Scott Pauley')—were planted on each plot in early 1979. The pine, false acacia and alder were 1 + 1 bare root transplants; the willow were rooted softwood cuttings, and the poplar unrooted hardwood cuttings. In all cases, the trees were notch-planted directly into the cover material with the minimum of cultivation. No fertilizer or irrigation was used to establish the trees, but they were kept free of weeds to a radius of approximately 0.5 m around each tree by a combination of hand and chemical weeding. Further details of this earlier experiment are given in Insley & Carnell (1982).

3. Methods

Temperatures at 0.3 m depth were measured at five positions in each plot (Fig. 2) commencing in January 1983 and thereafter repeated about every three months, using stainless steel-covered thermistors. These were placed into holes made by driving a bar 20 mm in diameter into the cover materials. Five minutes was allowed for the thermistors to equilibrate with their surroundings before readings were taken by Wheatstone Bridge.

Concurrent measurements of oxygen, methane and moisture content were made in August 1986 to examine their spatial distribution in relation to soil temperature. Soil moisture was also assessed in May 1986. Oxygen was measured using a Draegar Oxylarm 30 and methane with a GMI Gascoseeker Mk 1. Soil gas was extracted from 0.3 m depth through a soil gas probe manufactured by Research Engineers Ltd. Soil samples for moisture determination were taken at 0.3–0.4 m by Eijkelkamp "Dutch" auger, and weight loss measured after heating to 105°C overnight. Moisture contents were corrected for the variable amount of impermeable stone (flint) that the samples contained. Survival of all species, and the height of *Robinia,* the species best surviving in the experiment, were also measured in August 1986. Results were subject to analysis of variance using GENSTAT (Alvey *et al.* 1983); correlation matrices were also computed for soil, temperature, oxygen, methane and moisture content as measured in August 1986.

TABLE 1
The effect of cover depth and type on soil temperature (°C) at 0.3 m depth

Date	Depth of cover (m) 0.0	0.5	1.0	1.5	Material Clay	Compost	Interaction
November 1983	19	23	24	22*	19	25‡	†
August 1984	33	27	27	26‡	27	30†	NS
November 1984	17	18	19	18 NS	17	19 NS	NS
May 1985	21	16	17	18‡	17	19†	NS
September 1985	26	21	21	21‡	22	23 NS	NS
May 1986	18	14	14	15‡	15	16*	NS
August 1986	29	23	21	21‡	23	24 NS	NS

†: effect significant ($p<0.01$);
*: effect significant ($p<0.05$);
‡: effect significant ($p<0.001$);
NS: effect not significant.

more stable spatially. Nevertheless, evidence from more recent plots in 1986 shows that even 11 years after the landfill was finally covered, new hot spots were still evolving or becoming more pronounced.

4.3 Soil gas measurements

Figures 6, 7 and 8 show plots of soil methane, soil oxygen and soil temperature respectively for August 1986. Soil methane was present in some, but not all of the control plots, and occasionally detected in covers of 0.5 m and 1.0 m thickness (Table 2). Methane concentrations of up to 51% and 30% of soil atmosphere were detected on occasions in these two covers respectively. The inverse relationship between soil methane concentrations and cover thickness is highly significant ($p<0.001$). Soil oxygen is negatively correlated with soil methane, and increased in a range from 0–19% with increasing thickness of cover. Like methane, this relationship was highly significant ($p<0.001$). Low oxygen concentrations usually occur where high methane concentrations are found, and it is likely that oxygen has been displaced by methane at these sites. Oxygen may also have been consumed by the activity of methane-oxidizing bacteria (Hoeks 1983).

Across the range of cover types and thickness, both methane and oxygen were closely correlated with soil temperature, oxygen inversely so (Table 3). This result is not unexpected but the strength of correlation is important as it suggests that temperatures may be useful in the prediction of soil oxygen levels when direct means of measurement are unavailable.

4. Results

4.1 Soil temperature

Soil temperatures greater than 40°C at 0.3 m depth have been recorded on three occasions during the monitoring period. Temperatures greater than 30°C were recorded on six occasions in spring and summer months; even in winter, temperatures of 25°C were noted. Mean temperatures decreased with increasing cover thickness on five of the seven assessment dates (Table 1). The effect of cover type was less clear. The first measurements in 1983 showed that temperatures were significantly greater in compost than in clay, as noted by Carnell (1983), and this result has been obtained on three subsequent occasions. However, the difference in temperature now appears to be decreasing with the age of the site, and in 1985 and 1986 was only significant ($p<0.01$) in the late spring (May) when the ground began to warm up after winter. The difference in temperature between compost and clay covers is probably due to the different heat capacity and heat conductivity of these two materials. The compost is composed mainly of coal ash and had a considerably smaller dry bulk density than the clay (0.72 and 1.09 g cm^{-3} respectively; Insley & Carnell 1982). Heat conductivity is markedly higher with an increase in bulk density (Marshall & Holmes 1979), and hence heat generated in the landfill is more easily conducted to the soil surface through clay than compost (Carnell 1983).

4.2 Temporal and spatial variation in soil temperature

One of the original aims of soil temperature monitoring at Pitsea was to examine the rate of cooling as the strength of reactions within the landfill began to decrease (Fourt, personal communication). Figure 1 shows mean temperatures for clay and compost covers at 0.3 m depth over the three years of monitoring, and compares them with conventional soil temperatures taken at Writtle Agricultural College (National grid reference TL 677066), 23 km NNW of Pitsea. Results show that cover temperatures closely parallel natural soil temperatures, both showing seasonal effects. There is no evidence that non-landfill soil and landfill cover soil temperatures are converging, those at Pitsea remaining *c.* 6°C (range 3.0–10.1°C) higher over the three years of observation. It is unlikely that an increase of temperature of this order is detrimental to the tree growth, and soil temperatures at Pitsea may instead promote growth if optimum soil temperatures for plant growth (25–30°C) obtained by Richards *et al.* (1952) are applicable. Nevertheless, using mean temperatures conceals the fact that many plots have experienced temperatures between 30° and 40°C (e.g. in August 1984), when damage to tree functioning is likely to have occurred.

Plots of soil temperature residuals (Figs 3, 4 & 5) show the pattern of temperature after the effects of treatments have been removed from raw temperature measurements by regression analysis. In this form they give a good impression of the pattern of underlying or source heat. The plot for November 1983 shows a non-random distribution of positive and negative values. Comparison with later residual plots for November 1984 and September 1985 shows a slight shift in the temperature configuration from that established initially, but by then there had been some degree of stability in the temperature distribution. This suggests that in the first few years after the placement of cover materials over the landfill, the reactions leading to heat emanation are rather haphazard and unpredictable; only as the site matures does heat generation become

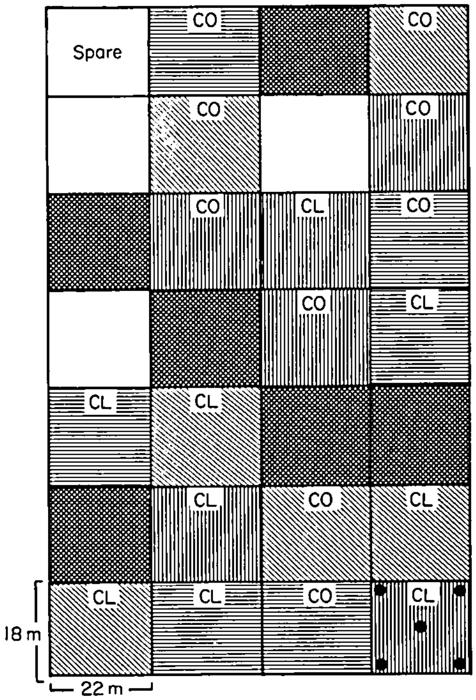

Fig. 2. Layout of experiment at Pitsea. Key: CL = Clay; CO = Compost; ▦ = Control; ▤ = 0.5 m; ▧ = 1.0 m; ▥ = 1.5 m; ● = monitoring site (example plot).

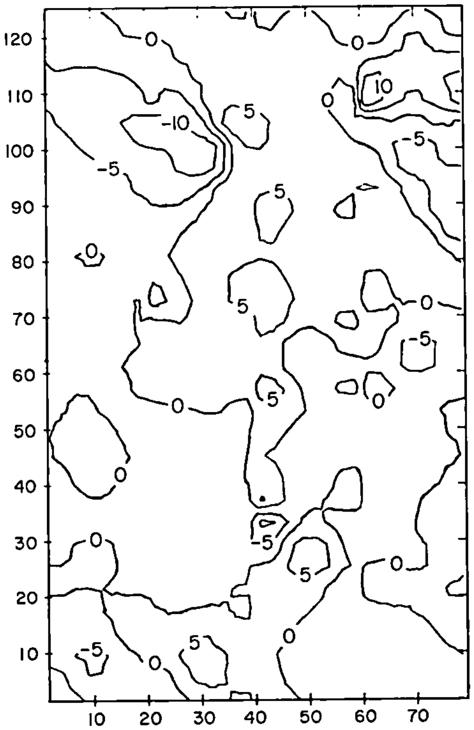

Fig. 3. Soil temperature residuals, November 1983 (°C).

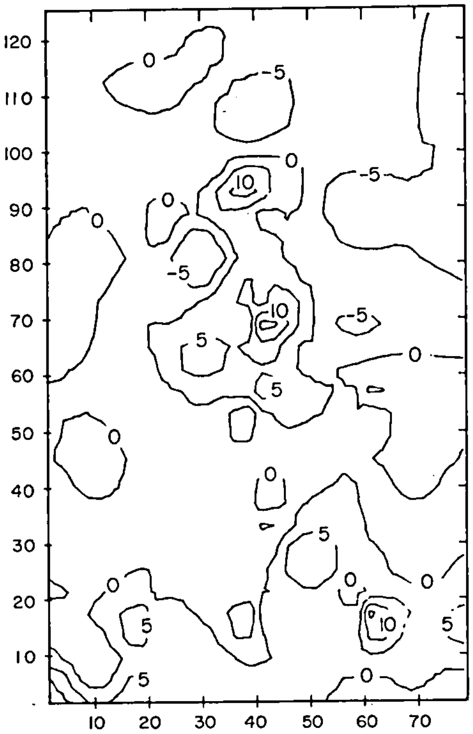

Fig. 4. Soil temperature residuals, November 1984 (°C).

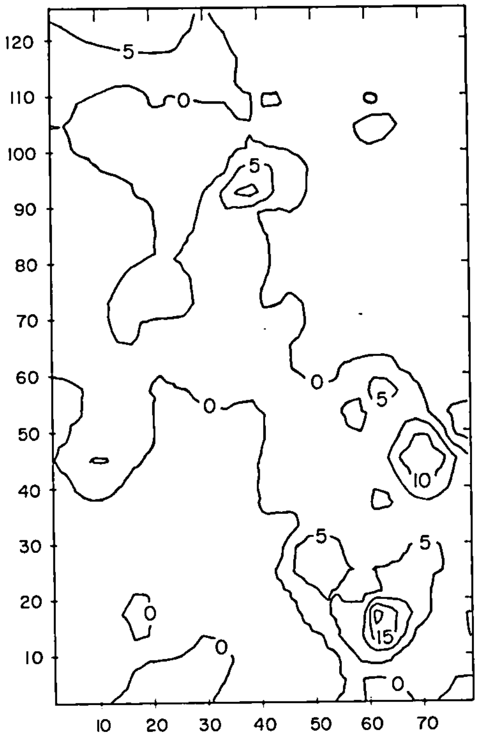

Fig. 5. Soil temperature residuals, September 1985 (°C).

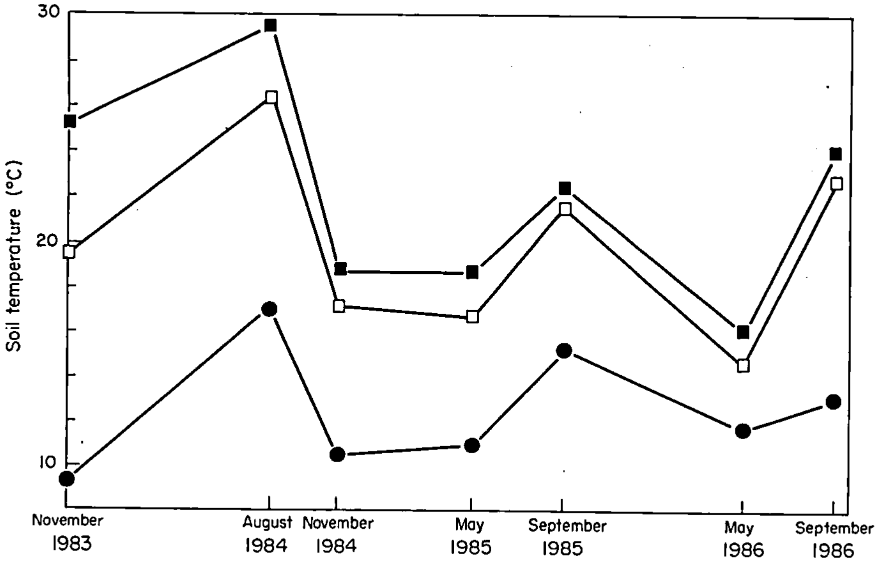

Fig. 1. Changes in mean cover temperatures November 1983–August 1986. Key: ■ = Compost; □ = Clay; ● = Writtle.

4.4 Soil moisture measurements

Soil moisture content varied significantly with cover type ($p < 0.01$) and depth ($p < 0.01$), decreasing particularly with increasing thickness. The clay held less moisture than compost. Moisture content was also significantly ($p < 0.001$) correlated with temperature and methane, and inversely correlated with oxygen (Table 3). The high positive correlation between water content and methane suggests that much of the water is coming from the underlying landfill, much of which is saturated (Holmes 1984). This moisture would be induced to move, mostly in the vapour phase, across the temperature gradient from high temperatures within the fill to cooler ones near the cover surface (Marshall & Holmes 1979). Enhanced levels of moisture in some plots may also be in part related to the low levels of soil oxygen in these plots which inhibit the growth of plants and hence moisture depletion through transpiration. This effect is, however, probably secondary to that proposed above.

4.5 Tree survival and growth

Figure 9 shows percentage survival of the five tree species eight years after planting. Compared with the results in 1980, two years after planting (Insley & Carnell 1982, Table 2), all species have suffered substantial death, particularly alder and willow. Tree survival was very low on 0.0 and 0.5 m covers for all species, but for all species except alder increased markedly on 1.0 and 1.5 m clay, though not on compost covers. Significant interactions between cover type and thickness were obtained for poplar and

TABLE 2
The effect of cover depth and type on soil physical properties in August 1986 (all measurements at 0.3 m depth)

Soil temperature (°C)	Cover thickness (m)			
Cover type	0.0	0.5	1.0	1.5
Clay	28.4	22.7	20.2	19.9
Compost	28.9	22.9	22.0	22.1
Soil oxygen (%)	Cover thickness (m)			
Cover type	0.0	0.5	1.0	1.5
Clay	4.7	16.0	16.6	17.8
Compost	2.1	15.2	11.9	16.6
Soil methane (%)	Cover thickness (m)			
Cover type	0.0	0.5	1.0	1.5
Clay	14.0	0.0	0.0	0.0
Compost	17.1	3.6	4.1	0.6

TABLE 3
Correlation coefficients (*r*) for soil physical properties (August 1986)*

	Temperature (°C)	Percentage oxygen	Percentage methane	Percentage water
All treatments				
Temperature (°C)	1.00			
Percentage Oxygen	−0.81†	1.00		
Percentage Methane	0.68†	−0.82†	1.00	
Percentage Water	0.64†	−0.72†	0.78†	1.00
Clay covers				
Temperature (°C)	1.00			
Percentage Oxygen	−0.74†	1.00		
Percentage Methane	0.67†	−0.89†	1.00	
Percentage Water	0.57†	−0.78†	0.85†	1.00
Compost covers				
Temperature (°C)	1.00			
Percentage Oxygen	−0.85†	1.00		
Percentage Methane	0.78‡	−0.77‡	1.00	
Percentage Water	0.76‡	−0.69‡	0.76‡	1.00

* Significance † $p<0.001$; ‡ $p<0.01$

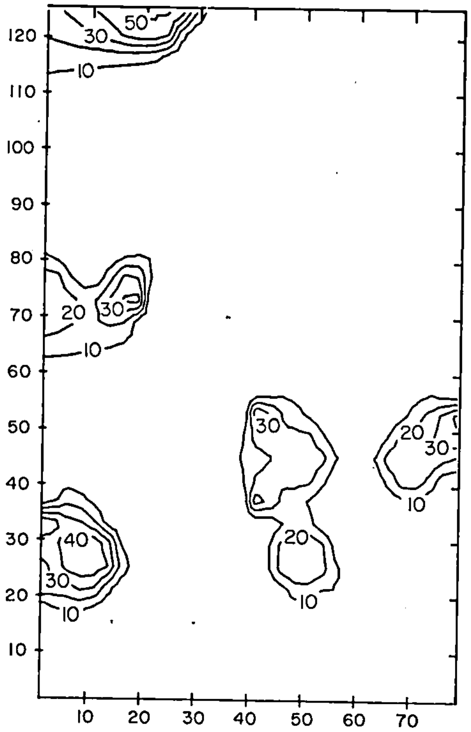

Fig. 6. Levels of soil methane, August 1986. Isopleths in percent.

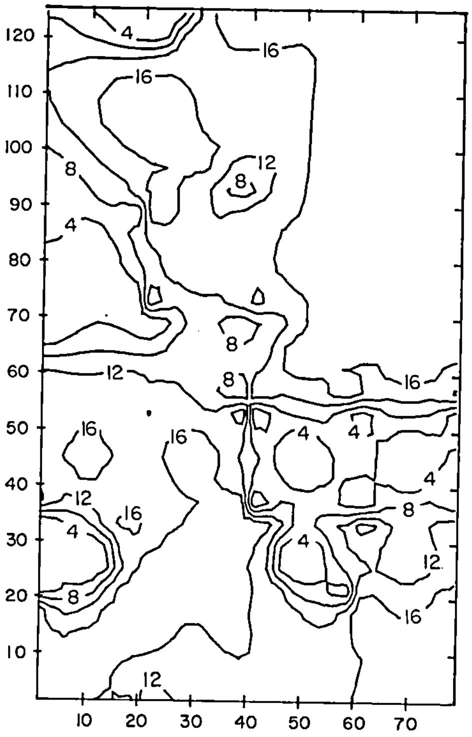

Fig. 7. Levels of soil oxygen, August 1986. Isopleths in percent.

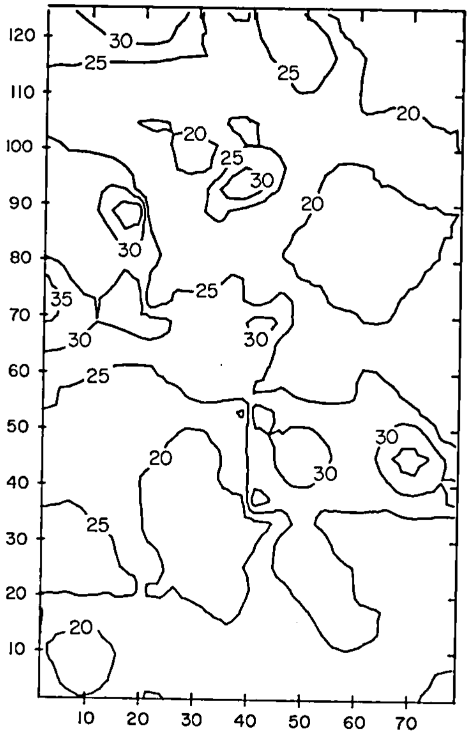

Fig. 8. Soil temperatures, August 1986 (°C).

Corsican pine, and significantly greater survival with cover thickness found in willow and false acacia. However, no species has survived well or acceptably on even the thickest covers; the poor survival of Corsican pine may, in part, be due to the use of 1 + 1 bare root stock, which performs poorly even in undisturbed soil (Coppock 1986).

Figure 9 also shows the mean height of *Robinia* in 1986. Trees growing in both clay and compost showed increased height growth with increasing thickness of cover.

5. Discussion

The main aim to date of monitoring soil temperature at Pitsea—namely to determine when soils cool, after fermentation begins to slow down within the landfill—has not been fulfilled. Temperatures remain significantly above those determined away from the site, and in many cases substantially so. In fact, anaerobic decomposition is likely to continue for the next decade or more (Shaw, personal communication) with consequent evolution of heat, methane and carbon dioxide. Nevertheless, for the majority of the experimental area, average soil temperatures are not critically high for plant growth although there may be short-term lethal temperature peaks.

High methane or carbon dioxide and low oxygen concentrations are probably the main causes of continued tree mortality in many of the plots with little or no soil cover. Methane is not in itself considered toxic to plants (Flower *et al.* 1981), but, with carbon dioxide, displaces oxygen from the root zone. It is not possible to specify a general minimum soil oxygen content required for plant root function and growth (Russell 1973), but soil with less than 12% oxygen is likely to be detrimental to tree health (Department of the Environment 1986) and soil with less than 6% certainly so.

Another likely factor affecting tree survival and growth is soil moisture. Average annual rainfall at Shoeburyness near Pitsea is low at 533 mm (Holmes 1984), and mean accumulated maximum potential soil moisture deficit is high, c. 225 mm (Hodge *et al.* 1984). Consequently, to ensure continued growth, vegetation needs a large supply of moisture from soil storage during summer months. Estimates of soil available water capacity (AWC) (i.e. water released at suctions of between 0.05 and 15 bar) using values from Hodgson (1976) and revised by M. J. Reeve (personal communication) show that only the 1.5 m thick clay, and 1.0 and 1.5 m thick compost covers have potential water reserves large enough to negate average soil moisture deficits. Hence tree survival is almost always best on the plots with thicker covers. Some species with particularly large water demands, such as poplar and Corsican pine (Binns 1980), perform very poorly unless soil depth is sufficient for total AWC to exceed the soil moisture deficit, and then survival is markedly better (Fig. 9). The generally poor survival rate on plots with 1.0 and 1.5 m compost cover, despite comparatively large moisture reserves, suggests an additional limiting factor, probably nutritional, is involved in these plots.

A feature of the Pitsea site today is the presence of an understorey of weeds. Originally bare of vegetation, many plots became lush with weeds (mainly grasses, umbellifers, brambles, nettles and other herbs), but no attempt was made to control them except immediately after tree planting. Davies (1987) has shown that such vegetation can seriously affect tree growth, particularly on sites with high moisture deficits and low available water capacities. Hence, lack of weeding at Pitsea has probably added to the other inhibiting site factors described above.

A number of suggestions for future tree planting projects on landfill sites come from this work. Of prime importance is the provision of an adequate thickness of rootable soil, or soil-forming, materials. Insley & Carnell (1982) found no significant increase in

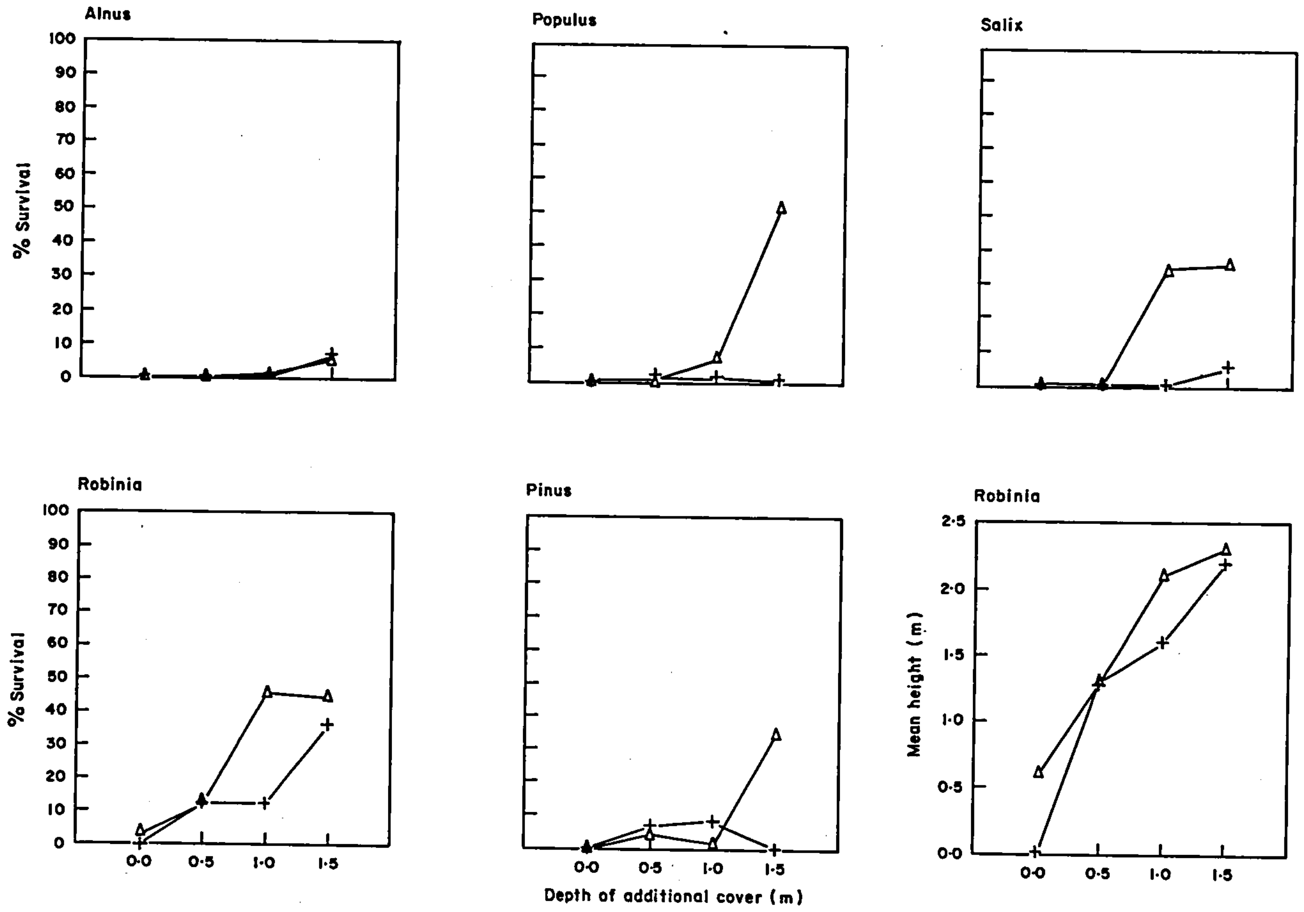

Fig. 9. Percentage survival of trees and growth of *Robinia*, August 1986. Key: Δ = Clay; + = Compost.

tree survival or growth (after two years) on plots with cover material thicker than 0.5 m, but recognized (p. 231) that "deeper covers would almost certainly be required for trees in the long term". This study has indicated that the addition of 1.5 m of cover can benefit some species substantially by providing a barrier to the movement of methane, carbon dioxide and other landfill gases into the root zone and so giving roots a more oxygen-rich environment to grow in than occurs on thinner covers. The results also indicate that soil cover thickness must be considered for the plant-available soil moisture it provides. However, more work is required in the U.K. to study: (a) the pattern of rooting of different species on domestic refuse landfill sites; and (b) measures to prevent the ingress of landfill gases into the root environment.

A major outcome of the study is an appreciation of the dynamic state of landfill gas and heat generation. A stable pattern in the emission of methane and heat appeared to take a number of years to develop at Pitsea; similar fluctuations in the generation of landfill gas over the short-term were observed by Spreull & Cullum (1987). Unless restoration procedures include the provision of materials to prevent ingress of landfill gases into the root zone (Department of the Environment 1986), preferably with the installation of a landfill gas venting system (Spreull & Cullum 1987; Her Majesty's Inspectorate of Pollution 1989), tree planting schemes may be best postponed until stability has occurred. Then trees can be planted away from methane-rich "hot-spots".

6. Conclusions

Several site factors have contributed to poor survival and growth on the experimental tree plots at Pitsea Landfill Site. High levels of landfill gas in the soil atmosphere and low soil available water capacities are regarded as the main causes of mortality, and the primary obstacles to tree establishment in the future. High soil temperatures may inhibit tree growth in localized patches.

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