Screening of trees suited for growth on landfill sites

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How to cite:

Gilbert Chan, Y.S. (1989) Screening of trees suited for growth on landfill sites. Masters thesis, Durham University.

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by

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Diploma (Hong Kong Baptist College), AMIWEM

A thesis submitted for the degree of Master of Science
in the University of Durham, England.

Department of Biological Sciences

November 1989

This thesis results are entirely from my own work and has not been offered in candidature for any other degree or diploma.

To God be the Glory

ABSTRACT

A field survey was conducted on the completed Gin Drinkers' Bay (GDB) landfill, Hong Kong, to investigate the causes of adverse tree growth. Ten tree species, belonging to eight families, were transplanted to two sites there. One site had a high concentration of landfill gas in the cover soil (high-gas-site, HGS), while the other had a relatively low concentration of gas (low-gas-site, LGS). Besides gaseous composition, general soil properties in these sites were similar. A strong negative correlation between tree growth and landfill gas concentration was observed.

A controlled laboratory simulation study was performed to study the influence of landfill gas on plants. The responses to gas varied greatly among species: some were very sensitive but others were tolerant. Generally, the growth of tap roots was reduced while the horizontal growth of adventitious roots was stimulated.

The results indicate that landfill gas does not have acute toxic effects on trees. The excessive quantity of CO_2 in cover soil limits the depth of the root system. Trees with a shallow root system become very susceptible to water stress. The effects of low O_2 concentration in soil are less important.

Trees suited for growth on sub-tropical completed landfill sites are listed, and their common characteristics are discussed.

ABBREVIATIONS

GDB	Gin Drinkers' Bay
HGS	High-gas-site (on Gin Drinkers' Bay landfill)
LGS	Low-gas-site (on Gin Drinkers' Bay landfill)
P	Probability
SS	suspended solids
t	t values of Students' t test, <ins>OR</ins> tonnes
TFS	total fixed solids
TKN	total Kjeldahl nitrogen
TS	total solids
TVA	total volatile acids
TVS	total volatile solids
VSS	volatile suspended solids

ACKNOWLEDGEMENTS

I would like to thank Dr M.H. Wong for his constant guidance and encouragement throughout the research period and Dr B.A. Whitton for his invaluable criticisms concerning the project especially at the final stage.

My thanks are also due to Dr V.W.D. Chui for her comments at the initial stage of the research project.

I would also like to thank C.Y. Lam for his advice in the field work, and K.C. Cheung and H.H. Choi for technical support in tree transplantation and soil analyses. Colleagues in the Hong Kong Baptist College helped in many ways, but especially I thank D.C.H. Pak for computer assistance and N.P.C. Pang for technical support with the gas chromatograph.

I am also grateful for the Sir Run Run Shaw Research Grant and the Faculty Development Grant of Hong Kong Baptist College. These grants gave me financial support during the project. The Biology Department of Hong Kong Baptist College provided places, computer facilities and instrumentation.

During the last two months of the project, in Durham, computer facilities in the Department of Biological Sciences were made available by Professor D. Boulter. I am very grateful to G.R.W. Hawley and M.A. Hall for their friendship and for proof-reading parts of the thesis. Special thanks are due to P.P. Jackson and S.L.J. Grainger for their technical support in the use of the computer, and to M.G. Kelly for discussion about statistics.

Lastly, I would like to thank my parents and my wife Grace, without whom I could never have completed this thesis.

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CHAPTER 1

INTRODUCTION

1.1 What is landfill?

Landfill is a method of co-disposal of waste and soil on land without causing nuisance to public health or safety. In Australia, Finland and U.S.A. it is called sanitary landfill to emphasize on the "sanitary" way of waste treatment (Chan, 1982, Ettala, 1987, Gilman et al., 1981b). It is also called municipal landfill to describe the origin of the waste (Berenyi and Gould, 1986). In the past, within the United Kingdom, the term "controlled tipping" was used, which emphasizes on the "controlled" manner of the dumping or tipping process (Gilpin, 1976); however, recently it has been called "landfill". In this thesis the term "landfill" is adopted and excludes those treatment activities for hazardous and radioactive wastes. Although the term "refuse" is sometimes used to describe the material dumped inside a landfill, in this thesis the term "waste" is used.

On a landfill site, after the waste is deposited on the ground, it is spread in thin layers and compacted by waste-moving equipment. At the end of each day the compacted refuse is covered with inert soil, and further compacted by steel wheeled compactors (Emberton and Parker, 1987). The purposes of the soil cover are to reduce rat, vector and odour problems, fire hazard and to improve the appearance of the landfill. Waste deposition and compaction followed by daily soil cover results in a series of horizontal refuse cells. Each layer of cell has 1 m of waste and 20 cm of cover soil, depending on the practice of filling works. After the horizontally available volume is filled, other series of cells are laid over the first; each horizontal series of cell is called a lift. The final top cover is a layer of soil about 20 cm to 1 m thick (Flower et al., 1981). Synthetic materials like urea-formaldehyde foam are sometimes used as an alternative landfill cover material (Graven and Pohland, 1987).

Valley fill is the most common filling method. Others include quarry fill and coastal dumping. To utilize fully the space, no matter what kind of filling employed, sites are usually filled to above the original land level or the water level and form a plateau (Flower et al., 1981; Wong et al., 1987).

Currently, landfill is not the only way of waste disposal. In contrast to landfill is the open dumping of waste; it is primitive and is the most simple method of waste disposal, but causes serious odour, vector and health problems. In poor countries, their waste production rate is low and open dumping is the most feasible way of waste treatment. However, in some developed or developing countries, waste is still not disposed of in a sanitary way in the current years e.g. only 65% of urban waste raised from Spanish towns received specific treatment in 1984 (Lema et al, 1988). Beside landfill, other waste treatment methods are becoming less favoured. Incineration causes air pollution, while composting and anaerobic digestion need skilful personnel to operate them. Furthermore, all other alternatives to landfill must be regarded as "volume reduction" processes because they all produce waste fractions which ultimately must be landfilled. Moreover, in comparison with other forms of waste disposal, landfill is an economic method. In the U.K., in 1983, the cost for landfill was £6 t^{-1}, incineration, £14 - £63 t^{-1}, composting, £45 t^{-1}, anaerobic digestion, £68 t^{-1} and pellet RDF £14 t^{-1} (Emberton and Parker, 1987). Due to the above reasons, landfill is becoming more popular in many countries. In the U.K., in 1983, 90% of all domestic, commercial and industrial waste was deposited in landfill sites (Emberton and Parker, 1987). In some other places, the percentage of waste disposed of by landfill are: Hong Kong, 66% (Pugh et al, 1985); Japan, 20%; West Germany, 70% (King, 1985).

To minimize transportation costs, landfill sites are usually close to the city from which the waste is collected. When a city expands in size, landfill sites are engulfed by urban development. The large area of completed landfill sites becomes very attractive for redevelopment. However, the redevelopment work is limited by two main reasons. The waste embedded in a site decomposes anaerobically and produce flammable landfill gas. There have been reports of gas being produced continuously up to 75 years after the burial of waste (Flower et al., 1981). As the waste degrades, it reduces in volume and the site settles. Therefore, the common practice is to reclaim completed landfill sites by converting them into parks, golf courses, botanical gardens, recreation areas or farmland (Gilman et al, 1982). Most of such development requires the establishment of vegetation. However, difficulties in such revegetating work has been experienced in many countries. The chemistry of anaerobic degradation of waste and the difficulties in development are described in detail in Sections 1.4 and 1.5.

1.2 Landfill in Hong Kong and nearby cities

Throughout the 1950s and 1960s waste arising in Hong Kong was disposed at open dumping sites such as Koon Tong and Gin Drinkers' Bay, located in the east and west corners of the Kowloon peninsula. This unacceptable practice was partially replaced by the commissioning of the Kennedy Town incinerator in 1968 and the Lai Chi Kok incinerator during the early 1970s (Boxall and Yung, 1984). In 1973, Gin Drinkers' Bay was changed into a landfill site; this was the first landfill in Hong Kong and eventually closed in 1979 (Wong et al., 1987).

Hong Kong currently produces over 11000 t d^{-1} of household, commercial and industrial wastes (Hong Kong EPD, 1989). Prior to burial, approximately 45% of the waste undergoes pretreatment in either one of the three incinerators at Kennedy Town, Lai Chi Kok and Kwai Chung, or the composting plant at Chai Wan (Pugh et al., 1985). Due to serious air pollution problems, all the above mentioned incinerators will be closed before 1991. The waste, whether pretreated or not, is ultimately deposited in one of the four operating landfills at Jordan Valley, Junk Bay, Pillar Point Valley and Shuen Wan (Fig. 1.1). However, these landfill sites are being filled rapidly and three will be full by 1989. Four public parks will be built on these sites after they are completed (Hong Kong EPD, 1989).

Hong Kong has long-term strategic planning for waste disposal. In 1982 the Hong Kong Government appointed the consulting engineers Binnie & Partners (Hong Kong), in association with Harwell Laboratory, to develop a comprehensive model for waste management planning. This model included one detailed physical

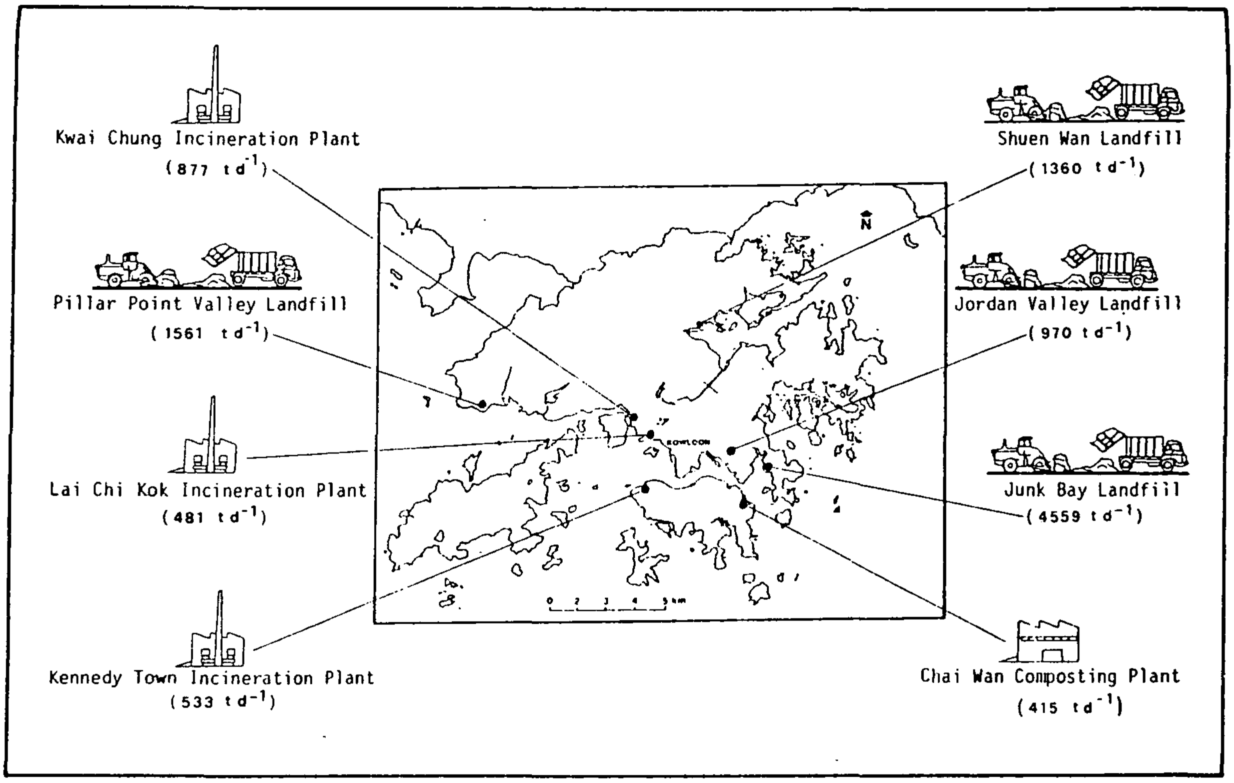


Fig. 1.1 Locations of waste disposal facilities in Hong Kong. (Hong Kong EPD, 1988)

data set on the existing and potential collection and transport systems, treatment plants and landfill sites (Pugh et al., 1985). The report also indicated that the amount of waste disposed at landfills and incinerators has been increasing by approximately 6% per annum. Plans have been drawn up for the establishment of three large strategic landfills to come on stream in the early to mid 1990s to meet the urgent need. These are Sent Landfill, Went Landfill and North Landfill (Fig 1.2)(Hong Kong EPD, 1989).

Hong Kong connects with the People's Republic of China (simply called China from now on) by land. This country has a population of 1.1 billion. Landfill has not been practised there for many years. In 1985, most of the waste collected in the cities of China was disposed by open dumping and only 1.6% of it was treated in a sanitary way (Chau, 1985; Chiu, 1986; Fung, 1985). Take Guangzhou as an example. This is the capital city of Guangdong province next to Hong Kong. It produced 1500 t of waste everyday in 1985 (Fung, 1985). In the decade of 1970, most of the waste collected in Guangzhou was disposed by open dumping in wild land, and mostly was dumped in any available land. However, in recent years China has started to employ landfill to dispose of waste. The first landfill site in Guangzhou was commenced in 1985 and other possible sites are being investigated (King, 1985).

Macau is a small Portuguese colonial city 29 km east of Hong Kong. It has a population of 0.35 million living on 16 km^2 of land. The daily waste production rate in Macau was 200 - 300 t in 1979. Open river dumping was employed between 1969 and 1983. Before then, refuse was transported to Guangdong and dumped there. Sanitary landfill has been employed in Macau from

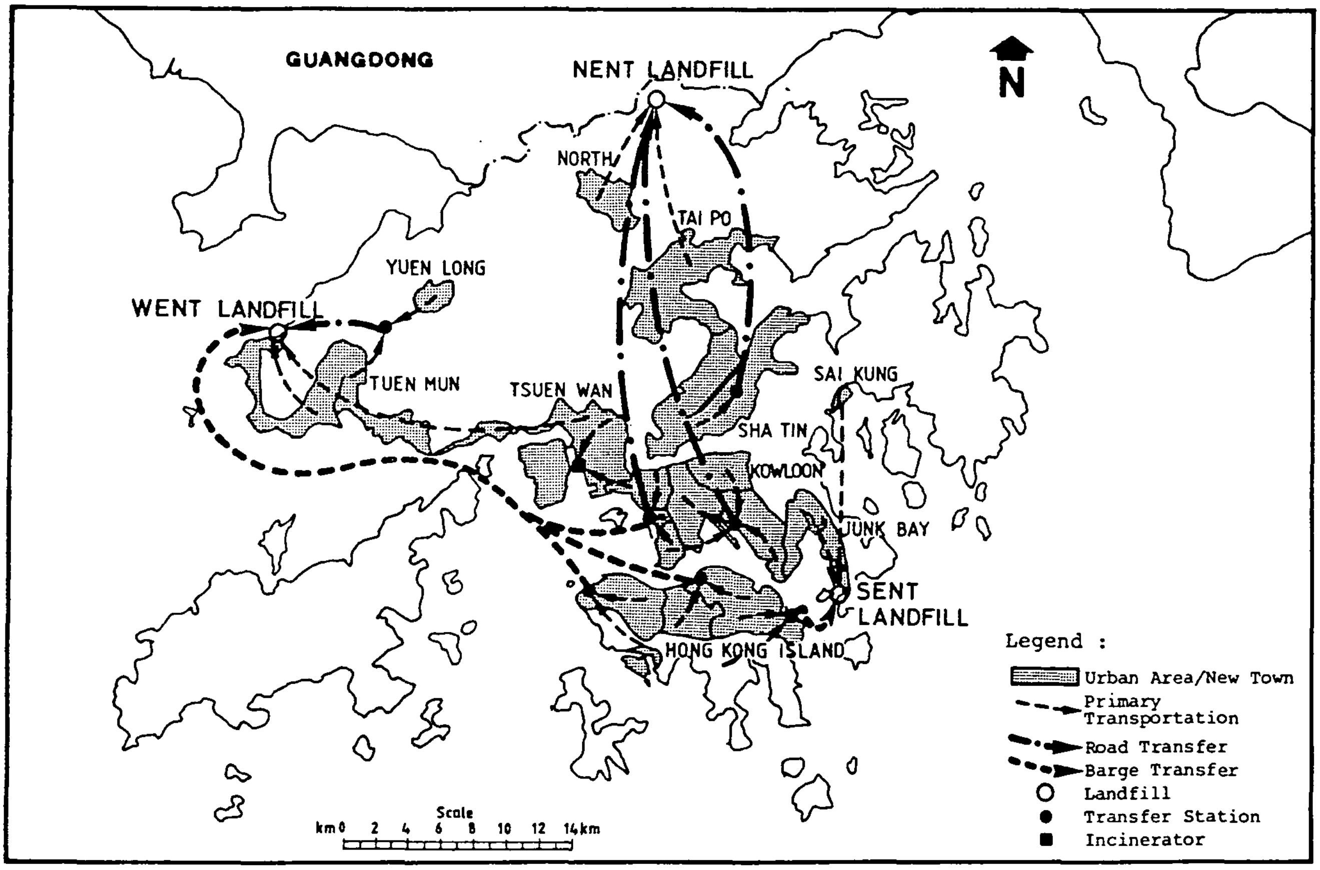


Fig. 1.2 Scheme for disposal of waste in the mid 1990s in Hong Kong.

(Hong Kong EPA, 1989)

1983 to the present day. Top soil was covered on the former open river dumping site and a revegetation programme started in 1983, which was completed in late 1985 (Wong and Lai, 1986).

As most of the landfill sites in China and Macau are still in use or recently completed, no difficulties in revegetating these sites have been reported.

1.3 Climate and tree communities on S-E. China and Hong Kong

As the project is to study tree growth on former landfill sites and uses a completed landfill in Hong Kong as an experimental site, basic information concerning the climate and natural tree communities on S-E. China, and the specific place of Hong Kong which is in the same phytogeographic region, should be introduced. The phytogeographic type of S-E. China is classified as tropical monsoon rain forest. It is a narrow belt-shaped region 250,000 km^2 in area along the southern edge of Fugien and Guangdong provinces and the whole of Hainan province. The mean annual rainfall in this region ranges from 130 to 350 cm. Winter is comparatively dry, with generally less than 10 cm of precipitation. It is hot in summer, with a July average of 27°C to 29°C and a January mean of 13°C to 21°C. Frost is virtually unknown in this region, except in high areas. S-E. China is always subject to summer typhoons (Richardson, 1966).

Hong Kong is located in the middle of S-E. China and its climate is typical of this region. Its latitude is between 22°9′ and 22°37′ N, and its longitude is between 113°52′ and 114°30′ E. It is a small hilly place covering 1068 km^2. The dry N-E. monsoon in winter causes the weather to be cool and dry from

October to April, and the prevailing S-E. monsoon results in hot and humid weather for the rest of the year. The mean daily air temperature ranges from 15.6°C in January to 28.6°C in July. Occasionally, the temperature will drop down to about 5°C in the winter and rise to about 34°C in the summer. The mean annual rainfall is around 222 cm of which an average of 86% falls from April to September. The maximum mean daily global solar radiation is in July and reaches 19.4 MJ m^{-2}. It declines gradually to a minimum in March, reaching 6.6 MJ m^{-2} (Royal Observatory, Hong Kong, July 1988 to June 1988 (monthly issues)).

A typical tropical monsoon rain forest in S-E. China is almost entirely evergreen. It has a high multiplicity of plant species, from tree to shrub, herbs, grasses, vines, epiphytes, climbers and other parasitic plants. Characteristic major tree species in this region belong to the families Myrtaceae, Moraceae, Lauraceae, Annonaceae, Leguminasae, Sapindaceae, Euphorbiaceae, Melastomaceae, Rubiaceae, Palmae, Theaceae and Fagaceae (Richardson, 1966).

Almost without exception, there are no places in Hong Kong where trees grow without human influence. Most of the rural areas in Hong Kong are leased to country parks. Selected trees are grown intensively there, especially after fires that commonly occur in winter. Trees commonly found on rural and suburban areas belong to the families Euphorbiaceae Lauraceae, Sarcospermataceae, Sterculiaceae, Moraceae, Myrtaceae, Rubiaceae, Elaeocarpaceae, Myrsinaceae and Aquifoliaceae (Wang et al., 1988). The Urban District Council (Hong Kong) listed 76 species of trees commonly transplanted to various sites in Hong Kong (Anon., 1989). Most are foreign species but they have superior growth in

Hong Kong. Detailed descriptions of these 76 and other tree species are available in Anon. (1976 and 1989) and Thrower (1979 and 1988). 10 species of tree, belonging to eight families, were chosen for the project and are described in detail in the next Chapter.

1.4 Anaerobic degradation

1.41 Chemistry

Waste decomposes in the landfill. Most of the organics are degradated microbiologically, and many metals corrode. At first, the landfill is aerobic, but becomes anaerobic after a few days. The organic breakdown involves facultative and obligate microbes. They are collectively called "methanogenic bacteria" (Klass, 1984). Fermentative bacteria are responsible for the primary breakdown of various polysaccharides, lipids and proteins into lower molecular weight intermediates. Hydrogenotrophic methanogens and acetogenic bacteria use hydrogen and acetate, respectively, as a substrate, and produce methane and CO_2. Methane constitutes 55 - 60% of the volume and CO_2 constitutes about 40% of the volume of the pure landfill gas (Flower et al., 1981; Spreull and Cullum, 1987)(Table 1.1). Landfill gas has other minor organic and inorganic components. Their concentrations depend on the waste embedded inside the landfill sites. The term "landfill gas" sometimes applies to the gas portion collected in the landfill cover soil, where the pure gas produced from microbes is diluted with ambient air which diffuses into the soil. Therefore, the commonly reported composition of landfill gas in soil consists of certain concentrations of

Table 1.1 Landfill gas composition at sites from different countries. [ND: Not detectable; tr: trace; $^{@}$collected from vent pipes; references: [1] Flower *et al.*, 1978; [2] Ettala, 1988a; [3] Wong *et al.*, 1987; [4] Sin, 1981; [5] Gilman *et al.*, 1982; [6] Walsh *et al.*, 1988; [7] Dernbach, H., 1985]

Gas	Unit	Edeboro, USA [1]	Finland (5 sites) [2]	GDB$^{@}$, Hong Kong [3]	Junk Bay Hong Kong [4]	New Jersey USA [5]
Methane	% - vol.	tr - 5.0	6.0 - 38	29.0	55.3	0.9
Carbon dioxide	% - vol.	1.4 - 18.1	3.5 - 19	12.6	28.2	5.5
Oxygen	% - vol.	15.8 - 19.6		4.5	1.3	17.8

Gas	Unit	Edeboro, USA [1]	Finland (5 sites) [2]	GDB$^{@}$ Hong Kong [3]	Junk Bay, Hong Kong [4]	New York [6]	West Germany [7]
Ethylene C_2H_4	$\mu l\ l^{-1}$	2.9		0.86			
H_2S	$\mu l\ l^{-1}$			1.94	21.0		
Chloroform	$\mu l\ l^{-1}$		0.042				
Tetrachloromethane	$\mu l\ l^{-1}$		0.10				
1,1,1-Tichloroethane	$\mu l\ l^{-1}$		0.17			0.001 - 0.140	<0.1 - 0.5
Trichloroethylene	$\mu l\ l^{-1}$		0.73			ND - 0.03	2.1 - 5.4
Tetrachloroethylene	$\mu l\ l^{-1}$		0.73			ND - 0.3	1.9 - 11.3
1,1,1,2-Tetrachloroethane	$\mu l\ l^{-1}$		0.024				
1,1,2,2-Tetrachloroethane	$\mu l\ l^{-1}$		0.030				
Hydrogen sulphide	$\mu l\ l^{-1}$		<0.10				
Benzene	$\mu l\ l^{-1}$					0.004 - 0.006	
Vinyl chloride	$\mu l\ l^{-1}$					ND - 17	
Toluene	$\mu l\ l^{-1}$					0.002 - 3.1	

nitrogen and oxygen. It has been estimated that up to $0.47m^3$ of gas may be produced for each kg of municipal solid waste that decomposes completely within the landfill. This would result in the total production of 260 unit volumes of landfill gas for every unit volume of refuse within a landfill (Flower et al., 1981). In terms of the yearly generation rate per refuse volume, Ham (1979) cites a range of 3.1 to 37 l kg^{-1} yr^{-1}.

Anaerobic degradation of waste in landfill does not only produce landfill gas as the final product. Landfill leachate is formed when water (generally precipitation) percolates through the waste and takes up the organic and inorganic intermediates or final products of the degradation process. Therefore, landfill leachate generally contains high concentrations of soluble organic matter and inorganic ions (Lema et al., 1988) (Table 1.2). Since gas and leachate have a common origin, leachate is saturated with landfill gas.

Five stabilization phases of the anaerobic degradation process may be identified in terms of principle events occurring during each phase (Pohland and Gould, 1986 and 1987; Pohland and Harper 1987) (Fig. 1.3). The first four phases take about 2 years. Phases I and II are transitional phases. Phases III and IV are particularly significant. The latter phase IV transforms intermediate products of hydrolysis and acid (phase III) to methane and CO_2. The final stage is the maturation phase where the gas compositions of methane and CO_2 become very stable. The total length of phases III to the end of phase V depends on the composition of the waste and also depends very much on intrinsic and external factors e.g. moisture and temperature.

Table 1.2 Landfill leachate composition at sites from different countries. [tr: trace; -: not reported; references: [1] Lema *et al.*, 1988; [2] Ettala, 1987; [3] Wong *et al.*, 1987]

	Unit	Ranges in landfills at 8 countries [1]	Hollola, Finland [2]	GDB, Hong Kong [3]
pH		3.7 - 8.5	6.6	7.6 - 8.2
Alkalinity		-	26.6	1048 - 5949
		-	[mek V l^{-1}]	[as $CaCO_3$]
Conductivity		-	312	7.6 - 32
		-	[mS m^{-1}]	[mmhos cm^{-1}]
COD	mg l^{-1}	40 - 48000	154	627 - 2873
BOD_5	mg l^{-1}	80 - 13000	2274	-
TS	mg l^{-1}	0.01 - 16.6	-	2670 - 9610
SS	mg l^{-1}	10 - 15000	221	-
TVS	mg l^{-1}	-	-	455 - 2040
VSS	mg l^{-1}	200 - 2000	-	-
TFS	mg l^{-1}	-	-	1450 - 8320
TKN	mg l^{-1}	170 - 1900	147	890 - 2177
$N-NH_3$	mg l^{-1}	0.0 - 3000	126	500 - 3358
$N-NO_3$	mg l^{-1}	-	-	0.4 - 92.0
$P-PO_4^{-3}$	mg l^{-1}	<0.5 - 80.0	0.77	0.2 - 4.0
Cl	mg l^{-1}	-	208	1160 - 3930
Total-S	mg l^{-1}	-	8.82	-
Ca	mg l^{-1}	-	230	12 - 27
K	mg l^{-1}	-	102	217 - 963
Mg	mg l^{-1}	-	-	62 - 129
Na	mg l^{-1}	-	156	784 - 2150
B	mg l^{-1}	-	1.9	-
Al	mg l^{-1}	-	4.5	-
Cr	mg l^{-1}	0.08 - 8.40	0.075	-
Mn	mg l^{-1}	0.1 - 125	58.5	0.2 - 2.3
Fe	mg l^{-1}	-	341	13 - 38
Ni	mg l^{-1}	0.01 - 6.11	0.04	tr
Cu	mg l^{-1}	0.0 - 9.0	0.095	0.12 - 0.48
Zn	mg l^{-1}	0.0 - 370	0.24	0.3 - 1.53
Cd	mg l^{-1}	0.0 - 0.45	0.0005	tr
Pb	mg l^{-1}	0.0 - 2.0	0.023	0.4 - 1.0

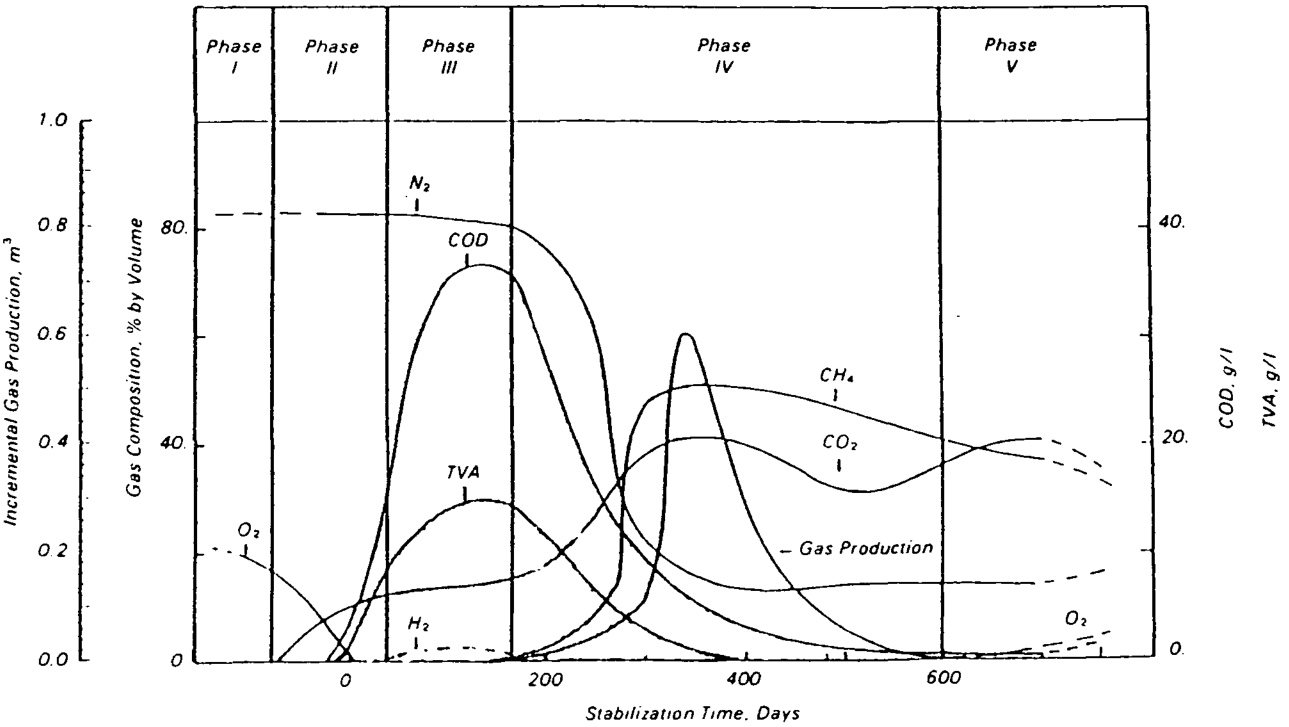


Fig. 1.3 Changes in variables during the phases of landfill stabilization (see Section 1.4). (Pohland and Harper, 1987)

1.42 Optimal conditions for the process

Acidic pH values below 6.0 inhibit methanogenesis completely (Siegal, 1987). The preferred alkalinity is about 5000 mg l^{-1} of calcium carbonate (Young et al., 1987). This concentration neutralizes the reaction materials and avoids the dangerous rise in the concentration of fatty acids, so that gas production is more stable. At room temperature (about 24°C) or at high temperatures (above 45°C), the gas production rate is low. The optimal temperatures for mesophilic digestion are 30°C to 35°C. The optimal C:N ratio for gas production is 20 to 30 and the optimal moisture level for gas production is about 87% (Polprasert et al., 1986; Wong, 1987). Higher moisture content can speed up the process, but gas production may not be stable, production may decrease rapidly and degradation is incomplete (Wong, 1987). Particle size and refuse density also are the major factors influencing methanogenesis (Siegal, 1987).

1.5 Difficulties in tree planting in completed landfills

Section 1.1 mentioned that usually there is a need to establish trees on completed landfill. However, adverse tree growth, includes high mortality rate, stunted growth and physiological disorders, has been experienced in many countries e.g. Finland, Ettala et al. (1988b); Hong Kong, Wong et al. (1987); USA, Flower et al. (1987); UK, Wong (1988). The presence of landfill gas in cover soil was suspected by the above authors as one of the main reasons for the high mortality and stunted growth of trees, but little is known about the influence of the gas on plants. In order to provide basic information relevant to the discussion, some general properties and physiological effects of the components of landfill gas are given in section 1.51. Section 1.52 gives information about non-gaseous factors which may affect tree growth. Section 1.53 reports the difficulties experienced in developing the first completed landfill site in Hong Kong.

1.51 Gaseous factors

1.511 Methane

Methane is an odourless gas (Spreull and Cullum, 1987) slightly soluble in water (Quinby-Hunt et al., 1986). It is the chief component among the anaerobically produced gases and has been identified in different environments including lakes, oceans, soils and groundwaters (Barker and Fritz, 1981). Methane is a hazardous gas, not because it is toxic, but because it may result in an explosive atmosphere (Walsh et al., 1988). When the concentration of methane in air is in the range 5% - 15%, an explosion may occur when a source of ignition is present (Emberton and Parker, 1987; Mohsen et al., 1978). The explosion threshold depends on the humidity. Methane is also an asphyxiant (Quinky-Hunt et al., 1986).

The production of methane in an aquatic environment and its effects on lower plants has been reported. Anaerobic degradation processes of bottom deposits cause high dissolved methane levels in sea or lake water (Wetzel, 1983). Methane was reported in the internal atmosphere of Elodea canadensis growing on a small pond rich in organic substrate. Under laboratory conditions, a high concentration of methane was noted in its internal atmosphere after five minutes methane bubbling, and the O_2 concentration within the plants decreased as methane diffused into the lacunas (Hartman & Brown, 1966). Methane can be transported from the roots to the atmosphere, or vice versa, through the lacunal system in floating aquatic plants (Wetzel, 1983; Morris and Dacey, 1984).

Although methane contributes up to 60% of landfill gas by volume and always has strong correlation with adverse tree growth on completed landfill sites, methane does not seem to exert any direct toxic effect upon vegetation (Flower et al., 1981). Ettala et al. (1988a) reported trees grown on Finnish landfill sites were not affected by 67% high concentration of methane in soil. Methane was considered inert to plants and was used as a tracer gas in transpiration study (Morris and Dacey, 1984). It was neither considered as a kind of secondary plant product nor a kind of material which could be metabolized by plants in the Encyclopedia of Plant Physiology (Ruhland, 1961). A computer search using the date base of Biological Abstracts 1974 to 1989, with "methane" and "root(s)" as key words, was done. This revealed 17 items, none indicated that methane exerted any direct physiological effects on vascular plants.

Methane does has indirect effects on plants. It can remove O_2 from the rhizosphere of vegetation by direct displacement, by utilization of the O_2 by methane-consuming bacteria, or by a combination of these (Leone et al., 1977a). Another indirect effect of methane is that it promotes the production of ethylene under anaerobic conditions (Jackson, 1985; Spreull & Cullum, 1987).

In some circumstances, the presence of methane is beneficial to plant growth. For some species adapted to the low O_2 environment, methane helps in maintaining the low O_2 concentration in water. Vlamis and Davis (1943) reported that rice bubbled with methane grew better than with air.

1.512 Carbon dioxide

Normal concentrations of CO_2 in soil atmosphere range from 0.1 to 2.0% (Fernandez and Kosian, 1987; Geisler, 1963) and sometimes reach about 10% in silty clay soil (Carr, 1961). Due to the much higher solubility and diffusion rate of CO_2 than O_2 and N_2, the CO_2 concentrations in the water film surrounding a root are expected to be higher than in the soil atmosphere (Geisler, 1963).

Carbon dioxide at moderate levels acts as a stimulating substance to roots. Aeration with air containing 5% CO_2 increased the root mass of wheat (Street, 1969). Geisler (1963) reported that a low level (30 - 200 mg l^{-1}) of dissolved CO_2 caused root elongation, and root thickening in peas. It was only growth accelerating and did not cause additional initiation of laterals.

Carbon dioxide concentrations above 15 or 20% are lethal to some plants (Chang and Loomis, 1945). The threshold for CO_2 exerts inhibition effects varied greatly among plants. Reduced root length was found in treatments with CO_2 levels higher than 100 mg l^{-1} in cotton, tomato, peas, oats and barley (Geisler, 1963). Absorption of water by the roots of wheat, maize and rice growing in water cultures was reduced 14 to 50% by bubbling CO_2

through the solutions (Chang and Loomis, 1945). Stolwijk and Thimann (1957) reported the growth of Pisum sativum, Vicia faba, Phaseolus vulgaris and Helianthus annuus roots were completely inhibited if the root media were aerated with 6.5% CO_2. The same report indicated that the susceptibility to CO_2 between monocotyledons and dicotyledons were different. Some specific toxic effects, to which oats and barley were immune, were exerted by CO_2 in dicotyledons. Leonard and Pinckard (1946) reported 39% saturated CO_2 in liquid culture reduced the root growth of cotton seedlings, zero growth was found at 60%, and the thickness of the root increased as the dissolved CO_2 level increased. Hook et al. (1971) reported that a two-month old seedling of sweetgum (Liquidambar styraciflua) survived 15 days in 2% CO_2 with only slight chlorosis, and growth was imperceptible. The seedlings died within 10 days in 31% CO_2 and within 15 days in 10% CO_2. In the same experiment, growth of swamp tupelo (Nyssa sylvatica) was not hindered by either 2 or 10% CO_2, but 31% CO_2 retarded root development, height, rate of O_2 uptake by roots, and the transpiration rate.

Some plants have a high tolerance to CO_2. A mixtures of gas containing up to 20% CO_2 passed into culture solution of barley had no apparent effect on salt uptake (Bowling, 1976). Roots of Vicia sativa and Pisum sativum tolerated 40% CO_2 for 28 hours if subsequently returned to a lower concentration (Carr, 1961).

1.513 Oxygen level

In a natural environment, anaerobic soil conditions are commonly established on soil with a high organic content and high humidity e.g. marshland. Flooding also results in low dissolved O_2 and an accumulation of CO_2. Whether in a marsh habitat or as a result of flooding, anaerobic microbial activities and respiration of plant roots releases CO_2 into the soil. The instances of low O_2 and also low CO_2 are rare. Some anaerobic conditions are man-made, such as paddy rice and other crop fields for water loving plants. These plants are adapted to low O_2 soil and flooding (Winchester et al. 1987).

Landfill soil is an unique habitat. Extremely low O_2 in landfill soil is caused by gas displacement and not caused by water immersion.

Higher plants, tolerant to low oxygen in rhizosphere, generally possess to one or two adaptive mechanisms. The first one is by the diffusion of O_2 from the atmosphere to the roots via the vascular system. For example, the roots of paddy rice may contain as much as 18% O_2 while the surrounding mud contains none (Vickery, 1984). Moreover, O_2 is also able to enter one root and be transported rapidly to another (Greenwood, 1969). The second method is by anaerobic respiration. The mature tissues of most plants can respire anaerobically for a short period of time (Hook et al., 1971; Leonard and Pinckard, 1946; Vickery, 1984). It had been demonstrated in the rhizomes of rice, Nuphar advenum, Phalaris arundinacea, Ranunculus flammula, Juncus effuscus, and Nyssa effusus (Hook et al., 1971). Anaerobic respiration begins when the O_2 content of the intercellular spaces drops to about 3% (Vickery, 1984). In most cases lactic acid may be a principle end-product of anaerobic respiration (Armstrong, 1975). Crawford (1967) has shown that within several genera, tolerance to prolonged flooding is related to the ability of an individual species to maintain metabolic control of ethanol production. Crawford also reported that intolerant species accumulated excessive quantities of ethanol under a low O_2 concentration, but tolerant species maintained a near-constant rate of accumulation, regardless of the O_2 concentration.

Some plants can tolerate a low O_2 level but others require a high O_2 level in soil for healthy growth (Leonard and Pinckard, 1946). The minimum concentration of O_2 tolerated by cotton roots has been reported to lie below 0.5%, and no root growth occurred under these conditions (Leonard and Pinckard, 1946). Tomato did not develop stress symptoms until the O_2 concentration began to drop below 4% (Flower <u>et</u> <u>al</u>., 1981). Some plants were reported to be relatively sensitive to a low O_2 soil environment. When the percentage of O_2 fell below 10%, there was a marked decline in the ability of barley roots to accumulate ions (Bowling, 1976). The growth of red and black raspberries and apple trees require 10% O_2 in the soil (Flower <u>et</u> <u>al</u>., 1981).

1.514 Other components

Beside methane and CO_2, minor fractions of other gases such as hydrogen sulfide, hydrogen, ammonia, nitrogen, carbon monoxide, ethylene, cyclic hydrocarbons and organosulphur compounds have also been reported present in landfill gas (see Table 1.1). The percent composition of these trace gases depends on the nature of the waste embedded inside a landfill and the concentrations of others. For example, high levels of volatile organic compounds, such as vinyl chloride (17000 nl l^{-1}), benzene (4-6 nl l^{-1}), toluene (2-3100 nl l^{-1}), trichloroethylene (30 nl l^{-1}), 1,1,1-trichloroethane (1-140 nl l^{-1}), and tetrachloroethylene (1-300 nl l^{-1}), were reported from a gas extraction system of a residential, commercial and demolition waste landfill (Walsh et al., 1988). The concentration of ethylene depends on the concentration of O_2.

Gases considered to be phytotoxins and found in landfill gas are ammonia, hydrogen sulphide, ethylene, ethyl mercaptan, benzene and acetaldehyde (Ettala, 1988a; Spreull and Cullum, 1987). Ethylene has many different effects on plants, including induction of adventitious roots, epinasty and control of flowering (Abeles, 1972; Beyer et al., 1984).

1.52 Other factors

Landfill leachate contains numerous acids, strong alkalis, organic and inorganic ions (Winant et al., 1981). A comprehensive comparison of landfill leachate in seven countries was reported by Lema et al. (1988) (see Table 1.2). Actually, leachate is a mixture of the soluble portions of any kind of materials embedded inside a landfill. High concentrations of leachate is harmful to the growth of plants and toxic to fish (Wong et al., 1987; Wong, 1989). It generally has a high nitrogen concentration and O_2 demand, whereas the phosphorus concentration is low (Ettala, 1987). Its heavy metal concentrations may be very high, as shown in Table 1.2. High levels of boron and total sulphur in landfill leachate were also reported (Ettala, 1987).

Anaerobic refuse decomposition at landfill sites releases heat and speeds up the chemical oxidation of the refuse. Continued chemical oxidation could then raise the temperature of the site (Emberton and Parker, 1987). Ettala (1988) reported that the substrate temperature was about 20°C and 15°C higher than normal soil temperature at a depth of 50 cm and 30 cm, respectively, in a Finnish landfill. Temperature elevation in landfill soil in cold places causes fewer problems for plant growth than in tropical places. For example, fewer difficulties were found in planting trees on landfills in Finland (Ettala, 1987, 1988a), but poor tree growth was experienced in New Jersey, U.S.A. (Flower et al., 1981) and in Hong Kong (Wong et al, 1987). Although the waste embedded in a landfill is self heated, the gas production rate also depends on the air temperature (Wong et al., 1987). Not only are the concentrations of major components of landfill gas (methane and CO_2) positively correlated with air temperature, Ettala (1988a) reported significantly higher levels of organic vapours in summer compared to winter.

As mentioned in Section 1.1, waste placement in modern landfill is compacted to maximize the site holding capacity and to minimize land settlement. Modern steel wheeled compactors may attain waste densities in excess of 1 t m^{-2} (Emberton and Parker, 1987). In the past, much less control over refuse placement was practised and refuse densities as low was 0.4 t m^{-3} were achieved. Theoretical settlement due to refuse decomposition is 40%. In practice, annual rates of settlement between 0.54% to

4.7% have been measured on sites of between 1.2 and 0.65 t m^{-3} placement density (Emberton and Parker, 1987). Generally, landfill sites should have been completed at least 10 years prior to redevelopment and tree planting (Emberton and Parker, 1987, Gilman et al., 1983). Settlement causes a change in leachate flow and landfill gas movement under the landfill cover. An area suitable for plant growth for years will suddenly become unsuitable due to leachate seepage and high landfill gas in the soil. It makes the revegetation work in the landfill more difficult. High bulk density, caused by over compaction, limits the penetration of roots and gaseous exchange in soil (Hopkins and Patrick, 1969).

Other non-gaseous factors such as lack of adequate soil moisture, thin soil thickness and low soil nutrient contents have also been identified (Ettala, 1987; Flower et al. 1981).

1.53 Problems experienced in Hong Kong

Poor plant growth was experienced in Gin Drinkers' Bay (GDB) landfill, the first landfill in Hong Kong (Fig. 1.4). It lies in the south-eastern part of Kowloon peninsula and faces the eastern coast of Tsing Yi Island, a small Pillar Island (Tsing Chau) situated at the mouth of the bay. The maximum depth of the channel located between Pillar Island and the mainland was about 13 m deep (Wong et al., 1987)

GDB was originally a small village for fishermen. In 1955, under the Ordinance No. 53, the bay was chosen for reclamation and open dumping (Boxall and Yung, 1984). In 1973, the Public Work Department (Hong Kong) took over the bay and changed it into

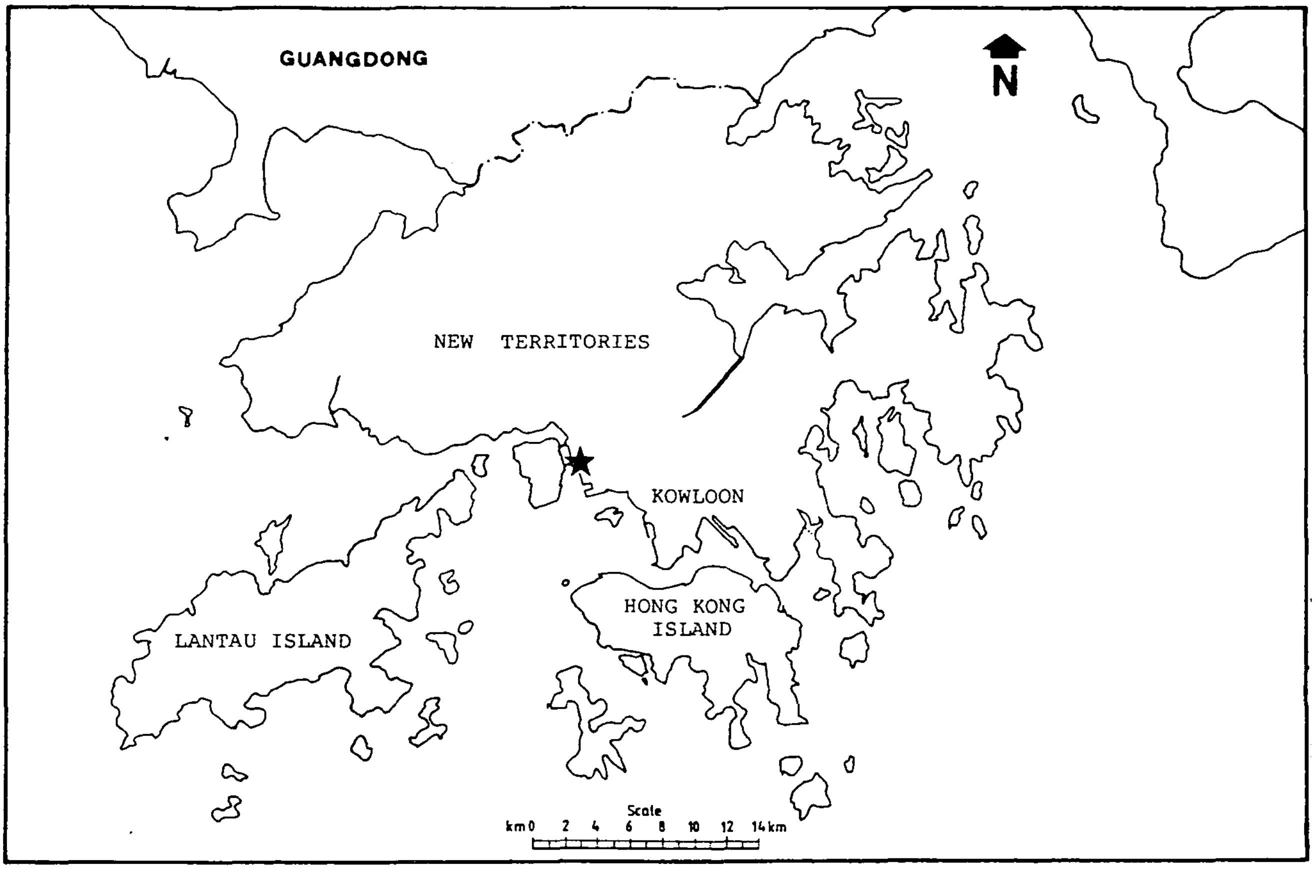


Fig. 1.4 Location of Gin Drinkers' Bay (GDB) landfill(★).

a landfill site. During the open period, waste was placed in 2-m layers and covered with 0.3 m of inert soil (Figs 1.5 and 1.6). The site was eventually closed in February 1979, at which stage a final covering of approximately 1.5 m of inert fill was laid on the area (Wong et at., 1987).

After 13-18 years of open dumping and 6 years of controlled tipping, a maximum elevation of 44 m was reached. With the original depth of the bay taken into account, the maximum depth of the landfill is about 57 m and the whole landfill plateau area is about 27 ha. The side slope has a gradient of about 20°. The exact amount of waste dumped during the uncontrolled open dumping period cannot be found. However, a contractor report (EBC(HK), 1982) estimated that about 8 X 10^6 m^3 of domestic and industrial waste had been filled there. The site has been closed for 10 years, and according to the Pohland and Harper's model (Section 1.42), gas production rate in there and methane and CO_2 concentrations in the cover soil should be very stable. An estimated amount of 0.36 x 10^6 m^3 d^{-1} (1.3 m^3 m^{-2} d^{-1}) gas was expected to be produced for at least 20 years (Whittaker and Rose, 1983).

In 1973, the suggestion was first made to convert the finished landfill area into a public park. In 1979 the EBC (HK)(1982) was appointed by the Government to investigate the feasibility for such a development (Whittaker and Rose, 1983). To minimize the problems associated with the migration of biogas and the percolation of leachate, several measures were undertaken. Sixteen vertical gas vent pipes joined together with an underground horizontal pipeline network were constructed on the

Fig. 1.5 A top profile of GDB landfill. The site was evacuated for the constructin of a foundation.

Fig. 1.6 A close-up of GDB landfill cover with the soil partially removed. The remain of waste, after embedded for about 10 yr, is mainly plastics, with the organics degraded. The cover was dug for lying water pipes and cables.

plateau so that the periodical monitoring of biogas was made possible. On the side-slope, gas migration was expected to be restricted by the relatively impervious soil layer. The leachate was diverted and collected by the sub-surface drainage system, discharged to foul sewers and finally discharged to coastal water via submarine outfall (Pugh et al., 1985). The site was hydro-seeded after completion and tree seedlings were transplanted there (Wong et al., 1987).

Following the implementation by the Government of the development of the landfill site into a recreation park, problems have been encountered as to the selection of plant species which can tolerate the landfill conditions. A detailed three-year (1984 - 1986) study was conducted by Wong et al. (1987) on this landfill. They reported the soil gas composition varied, depending on the sampling site (Table 1.1). A high correlation ($P<0.01$) was found between the concentrations of methane and CO_2. The O_2 content was found to have a negative correlation with the above two gases. The relative humidity of gas samples was also found to be correlated positively with methane and CO_2, and correlated negatively with O_2 ($P<0.01$). There was a strong negative correlation between the cover grasses, vines and herbs, with respect to landfill gas content. They also reported that the mortality rates of trees were high (Table 1.3). However, their results only indicated the overall performance of trees on the whole landfill site. The relationship between tree growth and soil gases concentration was not studied.

Table 1.3 List of trees planted on the GDB landfill. [[a]total number of trees planted on 1982; [b]number of trees replaced on 1983, assumed dead or in extremely poor conditions; source: Oriental Environmental Services, quoted by Wong *et al.*, 1987]

Species	Planted[a]	% dead[b]
Acacia confusa	1012	29.9
Albizzia lebbek	549	30.2
Aleurites moluccana	801	29.8
Archontophoenix alexandrae	543	29.5
Bauhinia variegata	671	24.4
Bridelia monoica	235	35.3
Celtis sinensis	340	48.8
Cinnamomum camphora	65	24.6
Cocos nucifera	87	4.6
Delonix regia	113	15.9
Ficus microcarpa	720	19.4
Ficus religiosa	508	49.2
Ficus variegata	156	44.9
Ilex rotunda	430	37.2
Litchi chienesis	49	93.9
Litsea glutionsa	948	55.4
Melastoma sanguineum	230	56.1
Paulownia fortunei	444	48.2
Rhaphiolepis indica	245	49.0
Rhododendron simsii	470	28.3
Rhodomyrtus tomemtosa	240	55.4
Sapium seberifum	186	58.1
Schima superba	407	47.4
Syzgium jambos	594	38.9
Toona sinensis	217	25.4
Tristania conferta	860	26.4

1.6 Aims

In the landfill environment, a high concentration of landfill gas in cover soil was suspected to be the major reason causing adverse tree growth (Section 1.51). Landfill gas is a mixture of methane, CO_2, O_2 and other gases. The effects of most of these individual gases on trees or other vascular plants were well documented. However, their combined effects under a landfill environment was uncertain. The overall emphasis of the research was to investigate the influence of key landfill factors on tree growth with special emphasis on landfill gas, and how to avoid their adverse effects.

The first aim was to study the relationship between key environmental factors and tree growth on landfill sites. A field survey of key environmental factors was conducted in Gin Drinkers' Bay (GDB) landfill, Hong Kong. Ten species of tree were transplanted to this landfill site and their relative growth on a high landfill gas area and a low gas area was compared. This would determine if landfill gas in soil was the most critical factor in affecting tree growth. A laboratory simulation study, with the field factors being controlled or being eliminated out, was conducted to investigate how landfill gas exerts its influence on trees.

A second aim was to identify common characteristics of trees suitable for growth on subtropical landfills. Through the above field and laboratory studies, the relative influence of adverse factors in landfill environment was revealed and superior features for trees which are suited for growth on landfill sites was identified.

CHAPTER 2

MATERIALS AND METHODS

2.1 Field Studies

2.11 Landfill gas detection

2.111 Set up of gas samplers

A 5-m wide belt transect was laid along the low-gas-site (LGS) and high-gas-site (HGS) in Gin Drinkers' Bay landfill (for details of sites, see Chapter 3). Within each transect, three 5 m x 2 m quadrats were set. They were about 10 m apart and represented the lower, middle and upper portion of the slope. Random quadrats of 1 m x 1 m were set within each 5 m x 2 m quadrat along the transects to install gas samplers, collect soil samples and also for the study of plant cover.

Three polyvinyl chloride gas samplers (Fig. 2.1) were installed on each 5 m x 2 m quadrat along each belt transect. In total, nine gas samplers were set on each of the LGS and HGS. The lower 25-cm portion of the 1-m gas sampler was perforated for gas movement between soil and sampler. A soil auger was used to dig holes and gas samplers were then inserted into the holes to 35 cm depth. The upper end of the sampler was sealed by a stopper with a glass tube. Rubber tubing was connected to the glass tube so that gas samples were collected directly from the sub-ground level into the sampler. The upper end of the rubber tubing was closed by a glass rod between samplings. Similar air samplers were used by Wong et al. (1987).

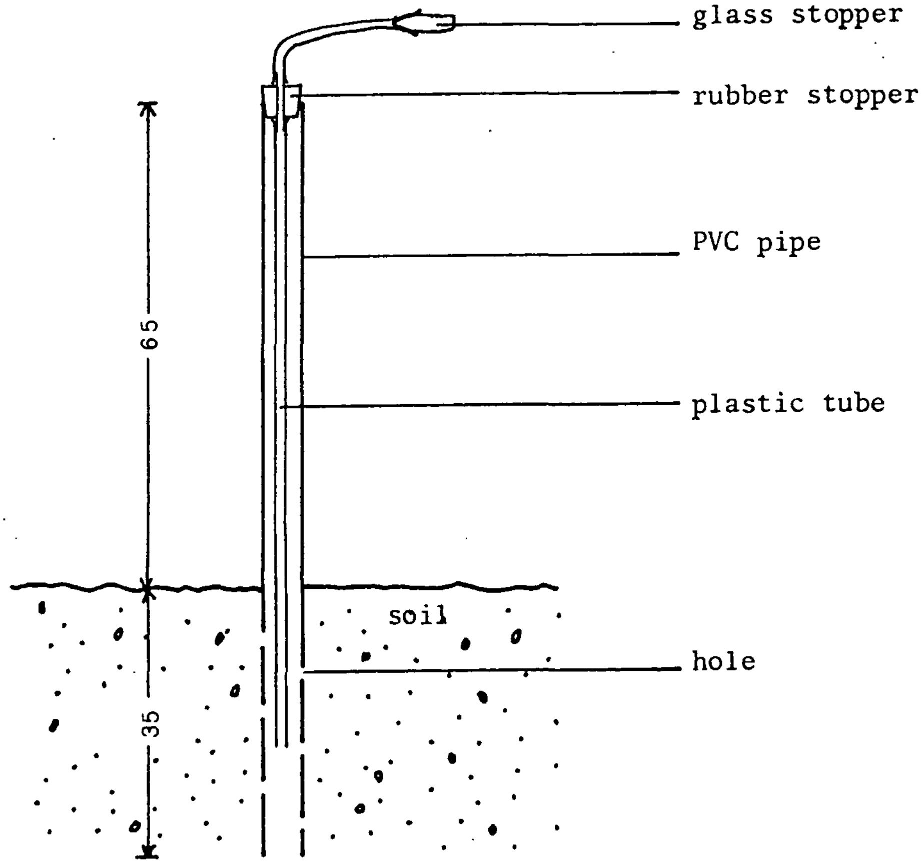


Fig. 2.1 Soil gas sampler installed in GDB landfill. (dimensions in cm)

2.112 On site measurement

Air samplers were set onto the ground at least one week before the air samples were analysed. Atmosphere within the sampler should be equilibrated with the soil air within this period. All gaseous samples in the project were measured as percent volume, unless specified. A portable combustible gas analyzer, Gasranger 73GR manufactured by Crowcon Inst. Ltd, UK, calibrated for methane in air, was used to detect the methane concentrations. The concentrations of CO_2 were detected by a gas aspirator Kitagawa model AP-1, adapted with dry-colour-detecter-tube model 126SH. The O_2 concentrations in soil gas were measured by an oxygen meter Kitagawa model OM-5. Detection of landfill gas was conducted in September 1988 and February, April and August 1989.

2.12 Soil analysis

2.121 Collection and preparation

Within each 1 m^2 quadrat, top soil samples were collected at 3 different points to depths from 2 to 10 cm, mixed up and stored inside plastic bags. They were transported to the laboratory for chemical analysis within 2 h.

Fresh soil samples were used for the determination of pH, conductivity and moisture content. The remaining soil samples were air-dried inside the laboratory, slightly homogenized by a mortar and pestle and were passed through a 2-mm mesh stainless steel sieve for nutrient and ion analysis.

2.122 Analytical methods

The variables tested and the methods employed were as follows: pH (1:1, w/w, soil to distilled water, measured by Kerno pH meter Model 671), conductivity (1:1, w/w, soil to distilled water, measured by a Fisher conductivity meter Model 152), loss on ignition (muffle furnace, 450°C for 4 h), moisture content (oven-dried at 105°C until constant weight), extractable phosphorus (extracted with Olsen's reagent, determined by stannous chloride-molybdate blue method, measured by Varian spectrophotometer Model 634, total Kjeldahl nitrogen (micro-Kjeldahl method), extractable inorganic nitrogen including ammonia, nitrite and nitrate (extracted with 2 M KCl, determined by steam distillation), total Na, K, Mg, Mn, Ni, Cu, Zn, Cd and Pb (digested by concentrated sulphuric acid and concentrated nitric acid (1:1), and then determined by a flame atomic absorption spectrophotometer, Varian Model Spectra AA 20). The methodology for these variables followed Allen _et_ _al_. (1974).

_In_ _situ_ soil temperature was measured at 6 random points on each transplantation site on a sunny day in early August 1989 using a 20-cm soil thermometer.

2.13 Sampling and analysis of plants

2.131 Plant coverage study

The percentage cover of all plants in each 1-m^2 quadrat was recorded. The plants were grouped into three categories: trees and shrubs; herbs and grasses; and climbers. As far as possible, plants were identified to the species level.

2.132 Collection and preparation

Above ground biomass, not including aerial intercepting tree branches, and the ground litter within each 1 m^2 quadrat were collected for dry weight determination. Fresh samples were stored separately inside plastic bags and transported to the laboratory within 2 h for analysis.

2.133 Analytical methods

The fresh weight of plant samples was measured. They were then dried at 105°C to constant weight, which was established within one week. The oven dry weights were measured. All mass of plant samples report in this thesis are in dry weight basis and measured by a top loading balance up to accuracy of an 0.01 g.

2.14 Tree species used in this project

Ten tree species (Table 2.1), belonging to eight different families, were selected for the studies based on their city tolerance, aesthetic landscaping purposes, susceptibility to landfill gas, tolerance to air pollutants and other criteria. Their general characteristics, mainly with respect to Hong Kong environment, and reasons for chosen in project are described as follows:

Table 2.1 Ten species used in laboratory and field studies, and criteria used for selection. [7m+: Over 7 m; 7m-: Under 7 m; Ae: Aesthetic landscaping purpose; Ap: Air pollution; Bs: Bad soil; Dr: Drought; E: Evergreen; Es: Exposed sites; F: Fast; Ft: Fire tolerant; Lt: Leaf leathery texture; M: Medium; Rs: Rocky sites; S: Slow; Sl: Slope planting; Sp: Salt spray; Ss: Shady sites; St: Shade tree; Tr: Transplantabiltiy; Ty: Typhoon tolerant; U: Ubiquity; Ws: Wet soils; +: indicates the positive degree of magnitude in that criteria; -: indicates negative degree; References: Anon., 1976, 1989; Man and Lau, 1986; Thrower, 1979 and 1988; Yeung, 1988a and b]

Latin name	Common name	Family
Acacia confusa	Acacia	Mimosaceae
Albizzia lebbek	Lebbek tree	Mimosaceae
Aporusa chinensis	Aporusa	Euphorbiaceae
Bombax malabaricum	Tree cotton	Bombacaceae
Castanopsis fissa	Chestnut oak	Fagaceae
Liquidambar formosana	Sweet gum	Hamamelidaceae
Litsea glutinosa	Pond spice	Lauraceae
Machilus breviflora	Short-flowered machilus	Lauraceae
Pinus elliottii	Slash pine	Pinaceae
Tristania conferta	Brisbane box	Myrtaceae

Latin name	General						Height		Growth rate			Extreme Conditions tolerant										
	U	E	Ae	Lt	St	Sl	7m+	7m-	F	M	S	Ap	Bs	Dr	Es	Ft	Rs	Sp	Ss	Tr	Ty	Ws
Acacia confusa	+++	+	++	++	-	+	+		+				+	++	+	+	+	-	--	--	++	-
Albizzia lebbek	+	-	+	-	+	+	+		+			+	+		+	-	+	+	-	+	-	-
Aporusa chinensis	+	+	-	-	-			+				+										
Bombax malabaricum	+++	-	++	+	-		+			+		+	+	++	+	-	-	-	--	+	--	+
Castanopsis fissa	+	+	+	++	-			+		+				-	-	-	+	-	-	-	-	-
Liquidambar formosana	++	-	++	+	-		+			+				++	+	-	+	-	--	+	++	+
Litsea glutinosa	+	+	-	++	-			+			+				+	-	+	+	+	-	++	+
Machilus breviflora	++	+	+	+	-			+														
Pinus elliottii	++	+	++	++	-		+			+		-			+	-	+	-	-	+	-	+
Tristania conferta	+++	-	++	+	+	+	+			+			+	++	+	-	+	-	+	-	++	+

Species 1: Acacia confusa Merr.

This acacia is a native of Taiwan and the Philippines. It grows well in Hong Kong, attaining a height of 6-15 m. Its alternate simple phyllode leaves are 6-11 x 1-1.5 cm, and rather leathery in texture. It is evergreen in Hong Kong and grows fast in almost any position, but does best in groups. Its leaf drop inhibits the growth of grass and makes the ground bare. Therefore it is commonly used for planting on hillsides but not in parks (Thrower, 1979 and 1988). It is an excellent wind-break and is typhoon tolerant, suitable for growth on exposed sites (Anon., 1989). It is also fire tolerant. It is not suited for shady sites, being salt spray sensitive and with a low survival rate after transplantation. It is one of the 11 most popular roadside trees planted in Hong Kong (Yeung, 1988a) and a potential tolerant tree for landfill conditions (Section 1.53).

Species 2: Albizzia lebbek Benth.

Lebbek tree is a native of tropical Africa and Asia reaching 15 m in height and with a wide spreading crown. Its leaves are alternate, compound (twice pinnate) with four to eight pinnae, each with 10-18 leaflets (Thrower, 1979 and 1988). The leaf stalk measures 7-10 cm with a brown oval gland near the base and attracts ant for feeding. It can withstand wind moderately well, tolerates poor dry soils and is tolerant to salt and thrives well on beaches (Thrower, 1979 and 1988). It is also resistant to atmospheric air pollution (Anon., 1989). It is suited for slopes and streets, commonly planted in urban areas for shade and ornament (Anon., 1989; Yeung, 1988a).

Both A. lebbek and the previous species of tree belong to family Mimosaceae. They are leguminous trees and root nodules provide nitrogen nutrients for them. Under normal growth conditions, their growth rates are fast (Anon., 1989). The growth rates of other eight species of trees in project are comparatively slow. Landfill soil usually are contaminated by landfill leachate which contains high nitrogen contents (Section 1.52). Nitrogen gas in landfill soil is displaced by landfill gas. Acacia confusa and Albizzia lebbek were chosen to study the growth of leguminous trees in nitrogen salts contaminated soil and in soil with low nitrogen gas content. Also, they were chosen to study the performance of fast growing trees under landfill conditions.

Species 3: Aporusa chinensis Merr.

Aporusa is a native tree, sometimes reaching 6 - 7 m, but much more often seen in Hong Kong as a moderate sized shrub. Short aporusa trees (4 - 7 m) are usually incorporate with other trees higher than 10 m. Its leaves are firm, but not leathery, alternate, simple, 8 - 15 cm long and about one-third as wide (Thrower, 1988). It grows well in poor drainage and nitrogen deficient soils. Although it is resistant to urban air pollution, it is not found in Hong Kong urban districts. It is, however, widely found in well established woodlands and on hillsides (Yeung 1988b). Aporusa is susceptible to insect damage

(Anon., 1976). It was chosen to represent the family Euphorbiaceae, a major tree family in S-E. China (Section 1.3).

Species 4: Bombax malabaricum D.C.

Tree cotton is widely distributed through India, Malaysia, South China, tropical Australia and Egypt (Thrower, 1988; Walth, 1971). It is a deciduous tree, growing to 25 m or more in height, with a straight central trunk and whorls of three to five horizontally spreading branches at intervals of about a metre. Its beautiful flowers are red. It flowers in April, before the new season's leaves, and is the first roadside tree in Hong Kong flowers in spring. Its mature leaves are alternate, compound, with five to seven elliptical 10 - 20 x 5 - 7 cm leaflets. It is resistant to city atmospheric pollution, tolerates wet soil and is also drought resistance. Lateral branches of B. malabaricum are subject to storm damage (Anon., 1989). It is one of the 11 most popular roadside tree species planted (Yeung, 1988a). It was chosen as this tree is very common in Hong Kong environment.

Species 5: Castanopsis fissa Rehd. & Wils.

Chestnut oak is a moderate fast-growing native evergreen tree reaching 6 m in height. Stiff and leathery leaves are alternate, simple, elliptical to obovate, 10-22 cm in length and 4-8 cm in width (Thrower 1988). Shade needs to be provided in early stages (Anon., 1989). In the recent years, the Hong Kong Government increased the use of this species for amenity purposes in urban parks. It was chosen to represent the large Fagaceae tree family in S-E. China. It is the only species within the ten species of trees in the project reported to be drought sensitive (Anon., 1989).

Species 6: Liquidambar formosana Hance

Sweet gum is a widely distributed deciduous tree with a range extending from S-E. China to Taiwan. In S-E. China, it may reach 40 m in height and 100 cm in diameter. In Hong Kong, no more than 10 m in height and 10 cm in diameter is found. It has resinous fragrant sap and corky branchlets. Its young leaves emerge in February. Mature leaves are alternate, simple, three-lobed, and 8-15 cm across. It prefers a sheltered moist situation (Thrower, 1979 and 1988) with deep good soil, but is also drought tolerant (Anon., 1989). Under natural conditions with less human influence, it is one of the most common shrubs and trees develop from a high-grass grassland (higher than 1.5 metres), suited for use in revegetation of land in south China (Chen and Mo, 1988). In the recent years, it has been used for afforestation in Hong Kong on account of its autumn red colour. Liquidambar formosana is the only Liquidambar species growing in Hong Kong. Gilman et al. (1981b) reported a Liquidambar species was not suitable for growth on a landfill site in New Jersey, USA. L. formosana was chosen to study the performance under Hong Kong landfill conditions, and to compare with their finding.

Species 7: Litsea glutinosa G.B. Rob.

Pond spice is native to Hong Kong. Its growth rate is slow and may finally attains a height of 10 m. Its leaves are alternate leathery, and 10 x 4 cm. It is salt spray tolerant. It thrives well in poor soils and stands fairly well to wind. It is, therefore, suited for growth on shady and exposed sites (Thrower, 1979 and 1988). In Hong Kong, it is commonly found incorporated with Pinus elliottii community (Cheung et al., 1988). It is of little ornamental value (Anon., 1989) and not commonly found on urban districts. It was chosen to study the responses of slow growers under landfill conditions. Among the ten species chosen in the project, only this tree and Aporusa chinensis are native to Hong Kong.

Species 8: Machilus breviflora Hemsl.

Mature short-flowered machilus is 6 - 8 m in height (Cheung et al., 1988). In Hong Kong, it is not easy to find M. breviflora growing in urban districts. It is, however, commonly grown in country parks (Thrower, 1988). Lauraceae is a big family in S-E. China (Section 1.3), M. breviflora and Litsea glutinosa are chosen to represent this family.

Species 9: Pinus elliottii Engel.

Slash pine is a North American pine with a pleasantly symmetrical conical crown. Mature P. elliottii in Hong Kong is 6 - 8 m in height (Anon., 1976). It is widely planted in country parks and suburban areas by the Government (Thrower, 1988). Due to its high survival rate after transplantation and high tolerance to rocky sites, it is used to landscape those arid sites after rock mining or on hillside areas in Hong Kong (Anon., 1989). P. elliottii was chosen for two reasons. It is the only species among the ten trees considered sensitive to atmospheric air pollution (Yeung, 1988b). It is the only gymnosperm used in the project.

Species 10: Tristania conferta R.Br.

Brisbane box is an Australian fast-growing evergreen tree, which grows well and reaches 15 m in Hong Kong. Juvenile leaves are opposite and simple, while adult leaves are alternate and compound. It suits a hot dry climate and withstands drought well. It grows well in any soil (Anon., 1989), commonly chosen for use when the soil conditions of a landscaping site are uncertain. It is therefore grown in urban areas and is also widely used in afforestation. In the country parks, it is often mixed with Pinus massoniana (red pine) and Aporusa chinensis (Cheung et al., 1988; Thrower, 1979 and 1988). Due to its superior growth in Hong Kong environment, it was chosen in the project as a potential tolerant species for landfill conditions.

2.15 Plant care

2.151 Transplantation

One to 1.5-year-old seedlings were obtained from the Tai Tong Nursery, Agriculture and Fisheries Department of Hong Kong.

Seedlings of the same species were of the same batch, sowed on seed beds on the same day and uniform in age. A few weeks after sowing, seedlings were transplanted to black polythene containers 5 cm in diameter and 15 cm in depth. Strong and healthy seedlings 20 to 30 cm high and with only one leader shoot (except Aporusa chinensis and Machilus breviflora) were selected for uniformity, and were transported to the greenhouse of the Hong Kong Baptist College in the summer 1988.

Intensive care was provided in the Government Nursery. Seedlings were watered three times daily, and shaded by overhead light reduction net on sunny days in the summer. The plants developed there were mesophytic and not suitable for transplantation to arid soil. It was necessary to change their leaves to a xeromorphic leaf type, otherwise the survival rate after transplantation would be low. To achieve this, tree seedlings were kept in an open space for an adaptation period of 2 - 4 weeks. During this period, light reduction net was not used and seedlings were watered only twice daily with minimal quantity of water. New leaves emerged after the adaptation period were smaller in size and much waxy than before.

After the mentioned adaptation period, tree seedlings were transplanted to the LGS and HGS on GDB landfill in a nested form in early July to early September 1988. Each species of tree had 10 replicates grown on LGS and HGS, respectively. In total, 200 seedlings were transplanted to the GDB sites. On the sites, holes of about 30 cm in diameter, 15 cm deep and at least 1 m apart were dug. About 5 g of 13:13:21 (N-P-K) commercial fertilizer was added to each hole. Polythene containers holding the seedlings were removed carefully by a knife, and roots with intact soil were put into the holes. The holes were then filled carefully with original soil and compacted. During a dry and hot summer day, the freshly transplanted seedlings rapidly became limp and damped. On such occasions, about 500 ml of tap water was added to the soil near the seedlings. In addition, each seedling was covered carefully by dry grass collected nearby; this resulted in a 30 to 50 % shading. The dry grass was removed after 7 days. As soon as the seedlings were transplanted to the GDB landfill, they were subjected to the fumigation of landfill gas and other landfill conditions. However, mortality of tree seedlings within 1 week seemed to be due solely to transplantation. The mortality rate of seedlings within 7 days was recorded to compare the ease of transplantation between different species.

2.152 After care

No irrigation system was present in any complete landfill sites in Hong Kong. Seedlings transplanted there by the landscape contractors were not irrigated even during a long period of drought. To compare the tolerance of trees under the "normal" landfill conditions, no water was applied to the experimental seedlings after the first day of transplantation. The only sources for them were rainfall, dew, landfill leachate and moisture from the degradation of refuse covered below. About 3 g of commercial uric acid was applied to soil once a month in the growth season beside each seedling. In order to observe the pattern and shape of tree growth, no pruning was carried out.

2.16 Growth measurements

Unless specified, growth parameters were measured on a monthly basis. The heights of the seedlings were measured from the ground level to the apical meristem tip to an accuracy of an 0.5 cm. Where there were more than one apical meristem tip, the highest was measured. The total number of mature leaves were counted for each seedling, except _Pinus_ _elliottii_. Subjective grades of plant growth (i.e. very healthy, healthy, fair, poor, very poor, dying) were recorded. Physiological abnormalities, infective diseases and insect bites, were described. Stomatal resistance of seedlings were measured using a porometer, Delta-T Device model AP3 on a sunny day in early November 1988; only those seedlings with healthy leaves were measured. The third mature leaf, or any one of the third pair of mature leaves, counted from the plant apex, was chosen for stomatal resistance measurement. At the end of the project period, base diameters of viable seedlings 1 cm above ground level were measured to within 0.1 mm. The same criteria in choosing leaves for stomatal resistance measurement were adopted in leaf size measurement. The length of the representative leaves and widths at quarters of the long axis were measured to 1 mm accuracy, and the their leaf sizes were calculated by approximation.

2.2 Laboratory studies

2.21 Generation of simulated landfill gas

Samples of pig manure were collected for gas production from Kadoorie Experimental Farm, New Territories. Pig feed used in this farm was well controlled, which resulted in a consistent quality of pig manure. The fresh pig manure with an initial moisture of 76% was composted for 3 to 7 days at ambient temperature (about 25 to 30°C) before use. White wood sawdust purchased from a factory in the New Territories was mixed with the pig manure to increase the C:N ratio for the fermentation process (see Section 1.42).

Pig manure and sawdust mixture was prepared (described below) and composted for at least one month and served as the seeding material. A starved methanogenic bacterial population in the seeding material helped to start the anaerobic degradation process.

The digester was modified from 25-l plastic tank (H x W x L = 50 x 20 x 30 cm). The opening was stoppered by a rubber cork with a glass tube connected to rubber tubing. A flow meter (see appendix) was connected to the other end of the rubber tubing to monitor the daily gas production rate.

Pig manure and sawdust at the ratio of 1.4:1 (dry weight basis) were mixed thoroughly with 6% seeding material in a digester. Each digester contained 5.4 kg pig manure, 1.06 kg saw dust, and 1.5 kg seeding material on wet weight basis. The exact composition of the digester is shown in Table 2.2. To provide

Table 2.2 Compositions of feeding materials for the digesters, and the contents of digesters.

	Pig manure	Saw dust	Seeding material	Calcium carbonate	Water	Total
Moisture content	76%	10%	90%	-	-	-
Volatile solid	74%	99%	-	-	-	-
kg dry solid tank^{-1}	1.3	0.95	0.15	0.13	-	2.53 kg
kg wet weight tank^{-1}	5.4	1.06	1.50	0.13	11.34 (87% moisture)	19.43 kg

optimal alkalinity and moisture for the fermentation process (Section 1.42), 0.125 kg of analytical grade calcium carbonate was mixed into each digester and adjusted to 87% moisture using tap water.

Preliminary studies showed a steady production of methane and CO_2 and no detectable ammonia and ethylene was achieved within one week. Therefore all the newly prepared digesters were placed in the laboratory and aged for about one week at room temperature (24°C ± 4°C) before use. Biogas production was steady during the first month of fermentation at room temperature. Each digester produced about 20 l of biogas daily. After about a month, digesters were immersed into a 35°C (Section 1.42) water-bath for another month to elevate the rate of gas production.

2.22 Design and construction of fumigation chambers

Fig. 2.2 shows the design and construction of fumigation tank. Biogas was fed into an acrylic gas diffusion chamber at the bottom of the tank via a plastic tube. A gravel layer, 4 cm in thick, made of 1-cm gravels, was set on the tank bottom. It served to fix the gas diffusion chamber in its position and for gas diffusion. A 13-cm thick garden soil layer was laid on top of the gravel layer, separated by a 2-mm mesh size plastic net. The soil used for filling all the 20 fumigation tanks was of the same batch, and had been passed through a 1 cm sieve. Each tank holds 10 seedlings, arranged to form a circle when viewed from the top (Fig. 2.3). Soil was filled into the tank and tapped with care. A gas sampler was embedded between the roots; it was

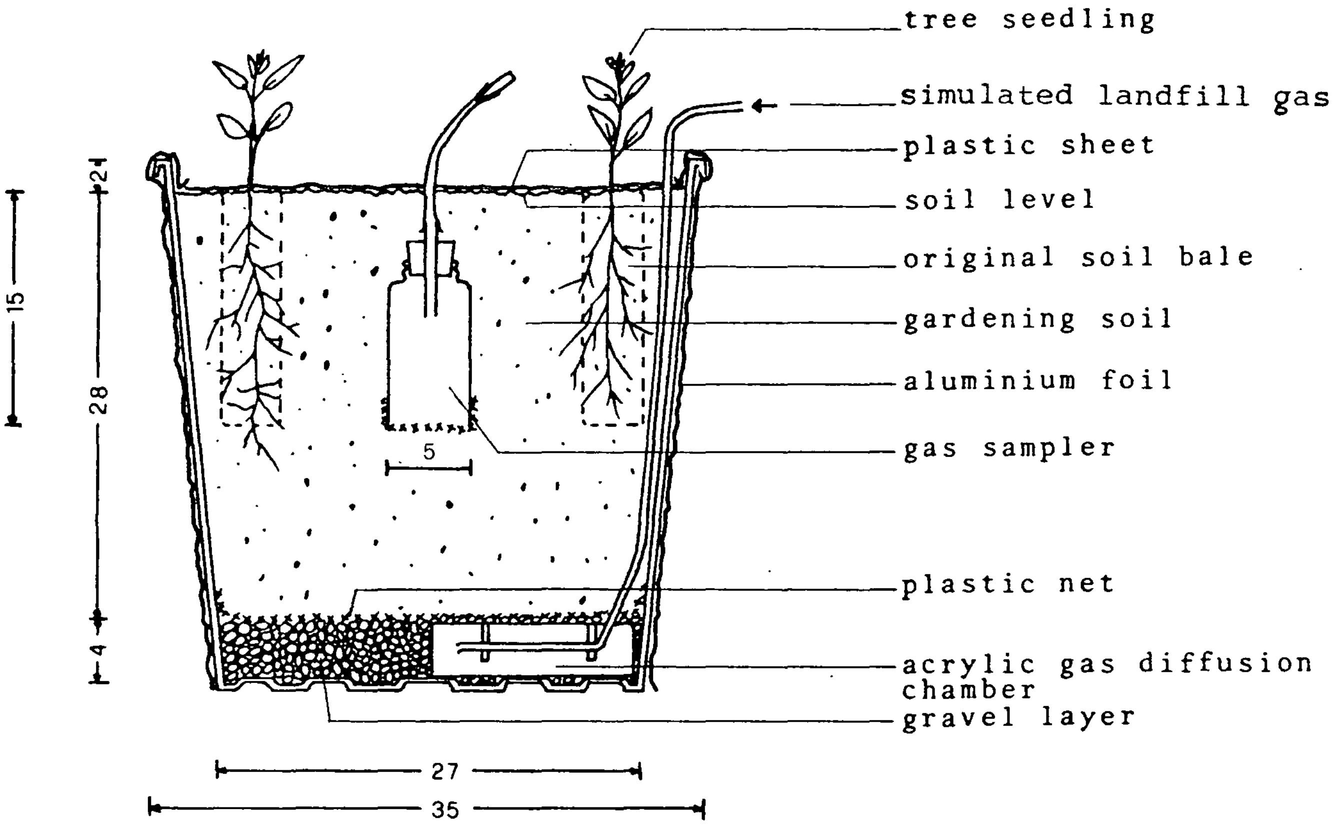


Fig. 2.2 Plastic pail used to study the influence of landfill gas on tree seedlings. (dimensions in cm)

Fig. 2.3 Pinus elliottii seedlings in fumigation tank.

a 60 ml tall form plastic bottle with the bottom removed and covered by a 2-mm mesh plastic net. The mouth of the bottle was stoppered with a rubber cork and connected to a rubber tubing for sample withdrawal. The degree of soil compaction highly affected gas permeability (Corey, 1986). Therefore, the air permeability of each tank was calibrated when seedling were packing into the tank.

The construction of the control tanks was exactly the same as the fumigation tanks. However, gas diffusion chambers and pipes embedded at the bottom of the tank were used solely for the air permeability test. No simulated landfill gas was fed into the tanks and the openings of pipes were closed throughout the whole experiment.

2.23 Method of fumigation

Preliminary studies indicated that there was a linear relationship between simulated landfill gas feed rate and soil gas concentration. Therefore, in order to maintain relatively stable concentrations of about 20% methane and 20% carbon dioxide for the 42-day continuous fumigation period, the gas feed rates were controlled within 35 - 45 l d^{-1}. In most cases, two 2-month old and two 1-month old digesters were connected to each fumigation tank via tubing and T-joints and passed through a gas volume flow meter. The volume flow meter (Appendix) was a modification of Mosey's device (Mata-Alvarez et al., 1986) and Triton Brand gas volume meter Model 181 which aimed at accurate and continuous measurements of a slow gas flow passing through a pipe line. When the soil landfill gas concentration dropped, an additional digester was connected to the fumigation tank; digesters used for more than 2 months were replaced by new digesters.

The gas production rate estimated on the GDB landfill was 1.3 m^3 gas m^{-2} d^{-1} (Section 1.53). It was an estimation for the whole landfill site. Gas emission rate would be especially high or low at certain areas. In project, the simulated landfill gas feed rate was about 0.6 m^3 gas m^{-2} d^{-1}.

2.24 Measurement of soil gaseous composition

Soil gaseous composition was monitored during the fumigation period. Gas samples were collected from the samplers (Fig. 2.2) installed in the fumigation tanks and the control tanks using 10 ml air tight glass syringes. The first 3 portions of gas samples collected were discarded to prevent dilution of ambient air trapped inside the connection between the gas sampler and syringe. The syringes were sealed with paraffin wax after sampling. Gas samples collected were analyzed within half an hour for the methane, CO_2 and ethylene levels by a Hewlett Packard Gas Chromatograph. The configuration and program for the analyses and operation of this machine are listed below:

Instrumentation: Gas chromatograph, Hewlett Packard Model 5890A
Detector: Thermal conductivity detector
Column: 2.5 m (8′) x 3.1 mm (0.125") stainless steel
Packing material: HayeSep Q, 80/100 mesh (Alltech, 1987)

Oven temperature: 50°C

Injector temperature: 150°C

Detector temperature: 150°C

Carrier gas: Helium

Flow of carrier gas: 30 ml min^{-1}

Soil gas contents were detected about twice weekly, depending on the availability of the machine. Since HayeSep Q cannot separate O_2 from other components, concentrations of O_2 were detected using a Kitagawa oxygen analyzer, Model OM-5. It was equipped with a suction pump and gas samples were drawn directly from the gas samplers of the tanks. This machine was also used for *in situ* measurement of O_2 concentrations in GDB sites. The ammonia levels in soil and in simulated landfill gas were detected using a Kitagawa gas detecter syringe model AP-1 adapted with disposable ammonia detecter tube model 105SD. Triplicate gas samples were analyzed.

2.25 Experiment conditions and plant care

Seedlings were grown in the laboratory with the temperature maintained at about 24 to 26°C and relative humidity 60 to 85%. Using fluorescent lamps and tungsten light bulbs simultaneously, the light intensity was adjusted to about 900 µmol photon m^{-2} s^{-1} and with a 16-h-light and 8-h-dark cycle.

The fumigation tanks and control tanks were watered daily with distilled water. Two hundred ml of half-strength Hoagland's solution (Ross, 1974) was added to each tank on the first day and once every fortnight during the study period. A soil moisture meter (Carolina Model 66-5494) was used to monitor the soil moisture content twice a week. All tanks were watered to the same magnitude of water content and the volume of liquid added was recorded.

2.26 Growth measurements

Plant growth of each tree seedling was determined once every fortnight during the 6-week study period. Leader shoot vertical heights, numbers of leaves, numbers of meristem tips, and other observable abnormalities were recorded.

After the 6-week period, aerial parts of the seedlings were cut for the determination of dry weight (Section 2.133). The whole tank was then immersed into water and soaked for half an hour before harvesting the roots. Preliminary studies indicated that immersing the whole tank into water minimized the damage to roots during harvesting, and was much better than the dry evacuation method. The biomass and maximum length of roots and root nodules (if any) were measured. Root growth pattern was recorded.

2.3 Statistics and computing

Differences between treatment groups and control groups were tested by student's t test at 0.05, 0.01 and 0.001 significant levels. A computer package, FRAMEWORK III, with a programme written by FRED commands, was used to calculate the t values. The method of student's t test calculation follows Bhattacharya and Johnson (1977) and Daniel (1987).

Text was typed using a word processing computer package WORD version 4.0 installed on an IBM Personal System/2 model 50Z. Tables were typed using FRAMEWORD III installed on the above machine. Computer graphics were produced by a graphic package Harvard with the above IBM computer. All text and figures were printed by Apple LaserWriter II NT laser printer.

CHAPTER 3

STUDY SITE

3.1 Geographical description

Two sites on the north-eastern slope of Gin Drinkers' Bay (GDB) landfill (see Section 1.53) were chosen for the project (Fig. 3.1). One had a low concentration of landfill gas in soil (low-gas-site, LGS) and the other had a high gas concentration (high-gas-site, HGS). They were approximately 10 m x 20 m and 50 m apart from each other. The slope had a gradient of 25°. The sites were situated in the middle of the slope, about 30 m from both top and bottom. Two ditches ran parallel to the long axis of the sites. One ran above the sites and the other ran below the sites. A third ditch ran along the slope and divided the sites. Therefore, the sites did not receive leachate seepage from upper soil in the slope. The surface run-off and leachate were collected by the ditches.

3.2 Environment of the sites

3.21 Introduction

North-eastern facing sites were chosen for special purposes. Typhoons attack Hong Kong in the summer and can blow from any direction; strong destructive winter monsoon generally blow from the north or north-eastern direction (Royal Observatory, 1988 and 1989). The air temperature may drop below 10°C under the winter monsoon. Cold air causes the death of seedlings of some trees. Young tree seedlings are more susceptible to low

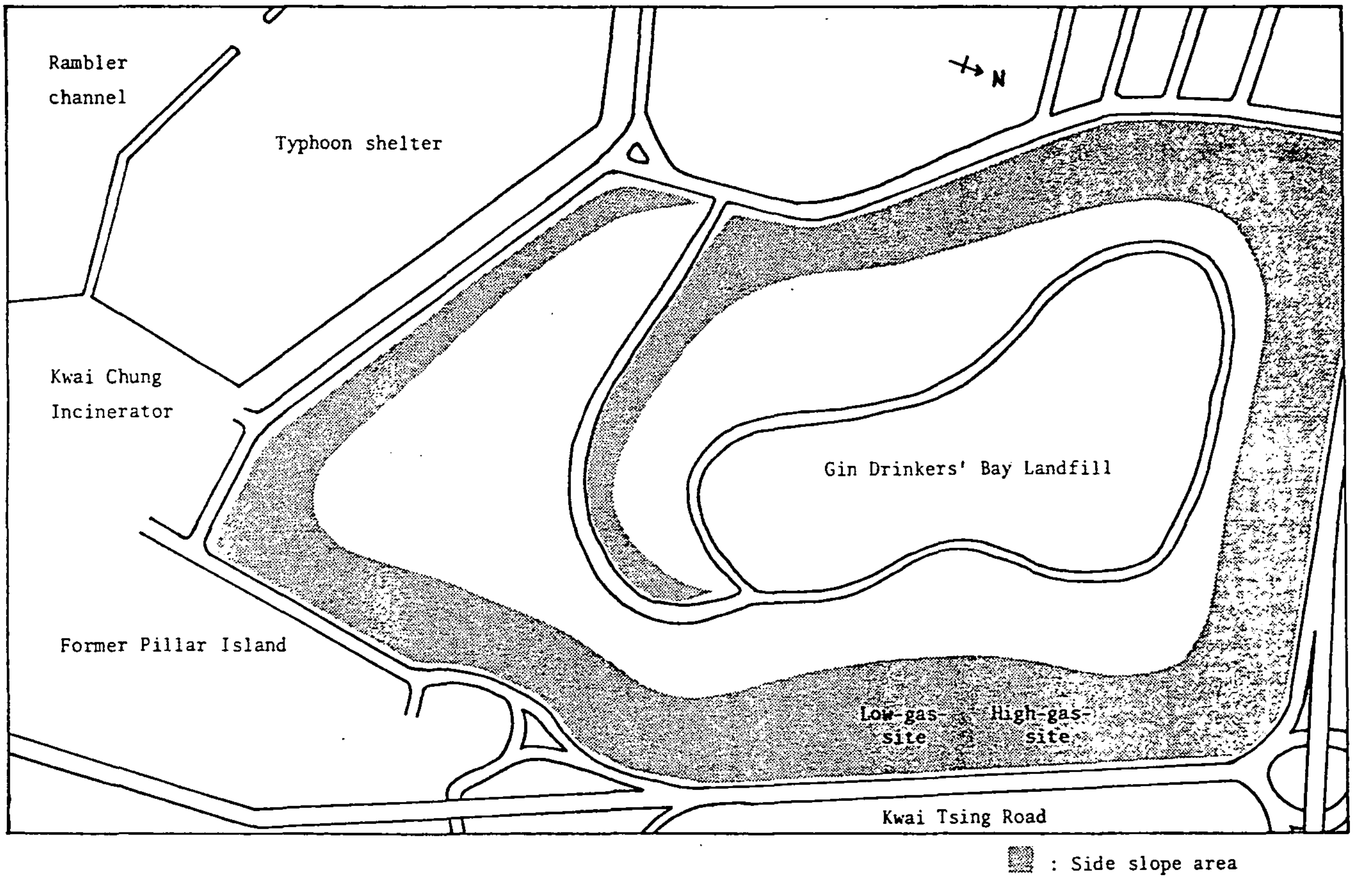


Fig. 3.1 Location of the Low-gas-site (LGS) and High-gas-site (HGS) in GDB landfill.

temperature. North-eastern facing sites were therefore chosen to study the growth of seedlings in the adverse climatic conditions in Hong Kong. Moreover, the site of the Hong Kong Terminal (the busiest container terminal in the world in 1988) was on the east of GDB landfill. It has a wide open space and is exposed to wind.

The sites were close to each other and were exposed to the same magnitude of sunshine, rainfall, wind and other climatic factors. As the sites were close, most of the field measurement works could be carried out at the same time and avoided spatial differences when using equipment operated by manual by the same person.

Throughout the project period, the GDB landfill site was a restricted area. The public had no access to the sites without permission and the experimental set up on the sites was subjected to little human influence.

3.22 Climatic factors

Data from four climatic factors were recorded on a monthly basis from July 1988 to June 1989 (the project period). They were the mean air temperature (°C), total rainfall (mm), mean daily global solar radiation (MJ m^{-2}) and total evaporation (mm)(Fig. 3.2). Beside these, the frequency of typhoons threatening Hong Kong was reported. Climatic data for the project period were compared with the means for the previous 30 years. All the above information were provided by the Royal Observatory of Hong Kong (Royal Observatory, 1988 and 1989).

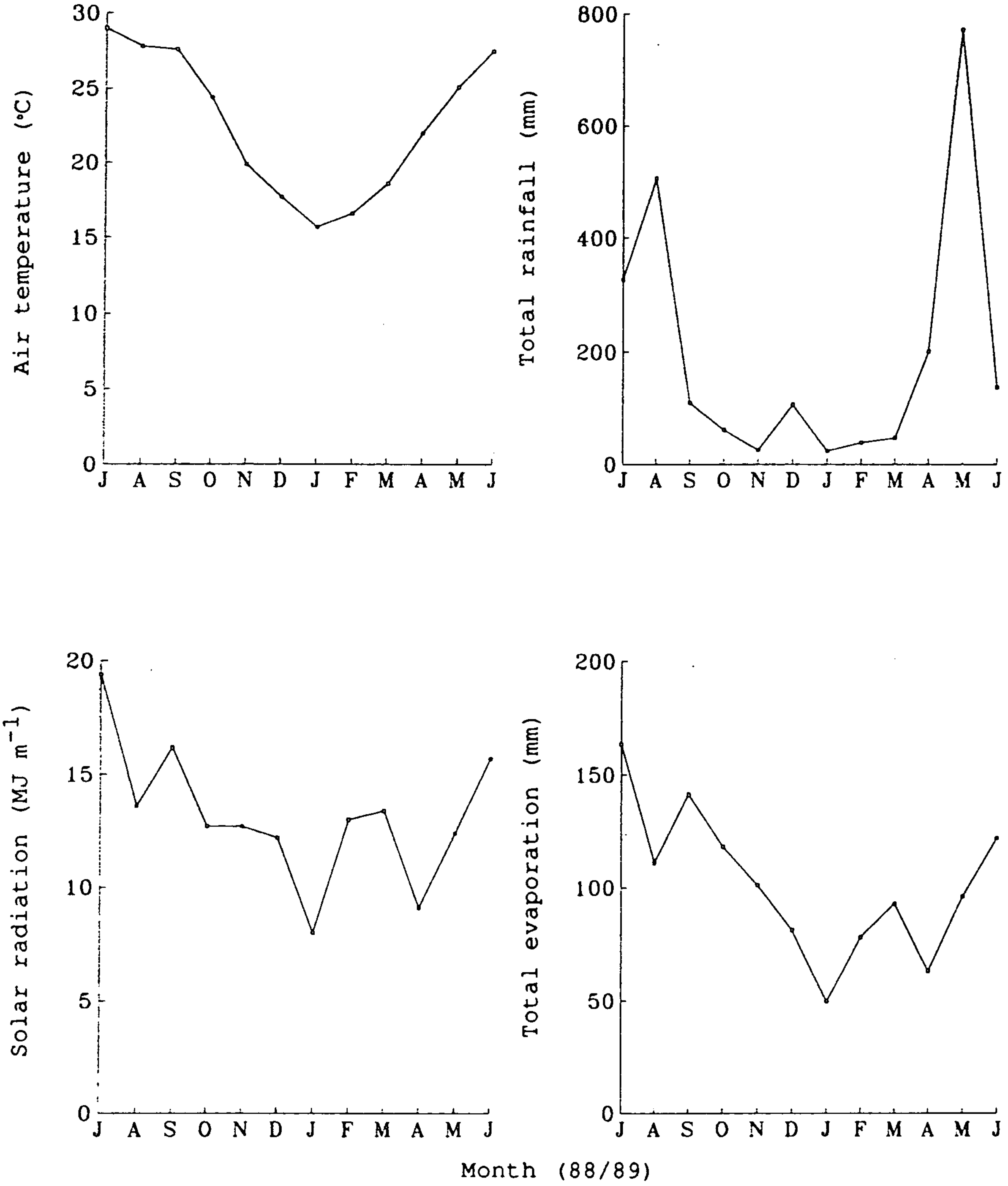


Fig. 3.2 Monthly variations in air temperature, total rainfall, solar radiation and total evaporation during the field study period (see Section 3.22).

Their equipment and sensors are located mainly in Tsimshashui Main Station, which is 5 km away from the project sites.

The mean air temperature in the study period was 22.7°C, very close to the mean in the previous 30 years (22.8°C). The daily range in air temperature did not exceed 10°C on any day within the project period.

The total rainfall in the study period was 2358.4 mm, 6.0% above the normal figure of 2223.8 mm. Rainfall in July and August 1988 was slightly above the normal figure by 3% and 22%, respectively. Although Strong Wind Signal No. 3 (average wind speed 22 - 33 km h^{-1}) was hoisted once in September 1988, the typhoon did not bring any significant amount of rain. The rainfall of 109.9 mm recorded in September 1988 was 66% below the normal figure of 320.4 mm. The 61.8 mm rainfall recorded in October 1988 fell short of the normal figure of 121.2 mm by 49% although two typhoons threatened Hong Kong in this month and necessitated the hoisting of the Strong Wind Signal.

The mean daily global solar radiation in the project period was 9.8% below the normal figure of 14.64 MJ m^{-2}. The maximum mean value was recorded in July 1988 (19.4 MJ m^{-2}) and the minimum mean value was recorded in January 1989 (8.04 MJ m^{-2}).

The mean total evaporation in the project period was 24.4% less than the normal. The trend of total evaporation within the project period was very similar to the change pattern of solar radiation over the same period.

No typhoon signal higher than No. 3 was hoisted during the project period. Typhoon signal No. 3 or below does not usually cause tree and construction damage in Hong Kong. In the 30 years' normal figures, Hong Kong had 3.1 days with a typhoon warning signal higher than No. 3 hoisted in a year. Thus, July 1988 to June 1989 was a exceptional year without any typhoon attacks.

3.3 Soil chemistry

Physical and chemical properties of soil samples collected from GDB sites were analyzed (see Section 2.12). The results of temperature, pH, conductivity, loss on ignition, moisture content, extractable phosphate, Kjeldahl-nitrogen, ammonia-nitrogen, nitrite-nitrogen and nitrate-nitrogen are summarized in Table 3.1. The pH of HGS soil samples was slightly acidic (pH=6.01), while soil samples from LGS were close to neutral (pH=6.49). The Kjeldahl-N, NH_3-N and NO_3-N concentrations in soil samples collected from the HGS were higher and nitrite-N was lower than the LGS soil samples. The values of conductivity, loss on ignition, moisture content and extractable phosphate in HGS soil samples were higher than in LGS soil samples. However, no significant difference ($P<0.05$) for the above variables were found between the soil samples from LGS and HGS. The soil temperature at 20 cm depth on HGS was 1.1°C higher than the soil temperature at LGS and a significant difference ($P<0.05$) was found between them. A high soil temperature of 45°C was detected at 20 cm depth on GDB landfill in summer 1988.

The total concentrations of Na, K, Mg, Ni, Cu, Zn, Cd and Pb in soil samples from HGS and LGS are shown in Table 3.1. There was no significant difference ($P>0.05$) for any of these metals between the HGS and LGS. The above findings show the chemical

Table 3.1 Physical and chemical properties of soil samples collected from GDB study sites.

[a, b: Distinct classes between the HGS and LGS, according to Student's t test, $P<0.05$;

all units are in mg kg^{-1}, unless specified]

Site	Temp. [°C]	pH	Conductivity [mS cm^{-1}]	Loss on ignition [%]	Moisture content [%]	P-PO$_4^{-3}$	TKN	N-NH$_3$	N-NO$_2$	N-NO$_3$
LGS $\bar{x}$	29.7b	6.49a	0.26a	4.01a	21.70a	20.90a	670a	15.05a	11.68a	37.21a
SD	0.8	0.69	0.18	1.36	7.11	5.97	308	13.48	21.42	21.33
HGS $\bar{x}$	30.8a	6.01a	0.42a	6.32a	23.80a	25.03a	1190a	31.35a	8.79a	98.38a
SD	0.4	0.55	0.31	2.96	8.05	8.74	829	24.78	11.63	78.35

Site	Na	K	Mg	Mn	Ni	Cu	Zn	Cd	Pb
LGS $\bar{x}$	105.7a	1648a	689a	655a	30.84a	18.96a	117.3a	4.23a	61.53a
SD	54.8	649	132	191	12.98	4.43	11.3	0.43	20.01
HGS $\bar{x}$	73.6a	1948a	573a	662a	28.17a	24.13a	125.2a	3.10a	48.65a
SD	16.0	805	174	155	5.63	10.70	39.0	4.13	9.98

matrix of soils (not including the gaseous component) in LGS and HGS were similar.

3.4 Above-ground plant growth

Plant samples collected on GDB sites and their percent coverage are shown in Table 3.2. The plants were grouped into three categories: woody plants, herbs and grasses, climbers.

A total of twelve species of tree intersected the quadrats on LGS and their total percentage cover was over 100% in each quadrat. Most of these trees were above 2 m high. Their canopies were thick and individual coverages were wide. Acacia confusa was the tallest tree on LGS, ranging from 3 to 10 m. Three species of tree, covered 7.6% of the total quadrat area on HGS: Acacia confusa, Celtis sinensis, Eucalyptus torelliana. Acacia confusa and Eucalyptus torelliana were also found on LGS. The general performance of trees on HGS was inferior to that on LGS. All trees were less than 3 m high, leaves were rare and the canopy cover were low.

Within the twelve species of trees found on the GDB sites, seven species were identified transplanted there for amenity purposes (Section 1.53). They were Acacia confusa, Bridelia monoica, Celtis sinensis, Delonix regia, Litsea glutinosa, Sapium sebiferum and Eucalyptus torelliana. Tree transplantation work was conducted on GDB landfill by the Hong Kong Government or by the landscape contractor in the past years. The other five species found on the GDB sites might be have been transplanted there or seeds were brought there by other natural means.

Table 3.2 Plant samples collected from GDB sites and their percentage cover. [Q1, Q2, Q3: quadrat number]

	LGS			HGS		
Tree and shrub	Q1	Q2	Q3	Q1	Q2	Q3
Acacia confusa	32.0	25.0	15.0	10.0		
Bauhinia purpurea			5.0			
Breynia fruticosa	8.0	36.0	11.8			
Bridelia monoica	0.6	23.0				
Celtis sinensis						4.9
Delonix regia	2.4		1.2			
Eucalyptus torelliana		0.8	35.0		8.0	
Lantana camara		35.0				
Litsea glutinosa	0.4	0.9				
Quercus sp.	0.1					
Sapium sebiferum	60.8	0.1				
Tristania conferta			55.0			
Subtotal:	104.3	120.8	123.0	10.0	8.0	4.9
Herb and grass						
Ageratum conyzoides	1.0	0.1	2.3			
Cynodon dactylon	3.0	0.3		5.0		1.0
Desmodium triquetrum	1.0					
Fimbristylis dichotoma					1.0	
Kummerowia striata					5.0	0.2
Neyraudia reynaudiana	10.0					
Panicum maximum	25.0	10.0		2.0		0.3
Panicum repens	40.0		50.0	60.0	60.0	70.0
Paspalum sp.				0.5	0.2	0.2
Subtotal:	80.8	10.4	62.3	67.5	66.2	71.7
Climber						
Cassytha filiformis	5.0					
Mussaenda pubescens				1.0		
Paederia scandens	20.0	0.5	1.0	1.0		
Passiflora foetida	5.0		15.0	12.0	0.5	5.0
Pueraria lobata	1.0					
Subtotal:	31.0	0.5	16.0	14.0	0.5	5.0
Total % cover:	216.1	131.7	201.3	91.5	74.7	81.6
% Bare ground:	0.0	0.0	0.0	8.5	26.3	18.4

Three out of the twelve species of tree found on GDB sites were chosen in the project and seedlings were transplanted to the sites for field studies. The species were Acacia confusa, Litsea glutinosa and Tristania conferta (Section 2.14).

The species diversity of herbs and grasses on HGS was equal to LGS (6 species on each site). The mean percentage cover by herbs and grasses were 51.2% and 68.5% respectively on LGS and HGS. The lower percentage cover by herbs and grasses on LGS was due to the high density of tree canopy cover on land and less sunshine was available for grasses. Moreover, leaf drop of trees can suppress the growth of grasses (Section 2.14)

The species diversity of climbers on LGS was higher than on HGS. Five species of climber were found on LGS whereas the number of climbers on HGS was three.

In total, all land in LGS was covered by vegetation. 17.7% of land on HGS was bare. The species diversity of vascular plants on LGS (22 species) was higher than on HGS (12 species).

The mass of above-ground plant parts and ground litter collected along the two transects are shown in Table 3.3. The mass of above-ground plant parts on LGS was 3.2 times the mass on HGS. The mass of ground litter on LGS was 3.0 times the mass on HGS. A significant difference ($P<0.05$) in mass of above-ground plant parts and ground litter between HGS and LGS was found.

3.5 Summary

The total rainfall within the project period was close to the normal figure. Rainfall in autumn 1988 was especially low.

Table 3.3 Mass of above-ground plant parts [excluding aerial intercepted tree parts] and ground litter collected from GDB sites. [a,b: Distinct classes between the LGS and HGS, according to Students' t test, P<0.025]

Material	Site	Quadrat 1	 2	 3	$\bar{x}$	SD
Mass of above-ground parts (g)	LGS	1127	2186	861	1391a	701
	HGS	304	234	783	440b	299
Mass of litter (g)	LGS	956	387	588	644a	289
	HGS	206	243	203	217b	22

Total solar radiation was close to normal figure whereas total evaporation within the project period was much less than the normal figure. No significant difference in chemical and physical properties (not including soil gaseous component) was found between soil samples collected from HGS and LGS in GDB landfill. The soil temperature at 20 cm depth on HGS was 1.1°C higher than the temperature on LGS ($P<0.05$). The species diversity and percent coverage of vascular plants on LGS was higher than on HGS. The mass of above-ground plant parts and ground litter on LGS were about 3 times the mass on HGS.

CHAPTER 4

FIELD SURVEY OF KEY ENVIRONMENTAL FACTORS AND PHYSIOLOGY OF PLANTS AT THE LANDFILL SITES

Adverse tree growth in the completed Gin Drinkers' Bay (GDB) landfill was suspected to be caused by the landfill gas in the cover soil (Section 1.53). In order to collect field data concerning the relations between tree growth, soil gaseous concentrations and other key environmental factors, an one-year field study was conducted there from July 1988 to June 1989.

4.1 Soil gaseous composition

Nine gas samplers were installed on each of the low-gas-site (LGS) and high-gas-site (HGS) (Section 2.111). Soil gas concentrations were measured four times during the project period. The overall mean concentrations of methane, CO_2 and O_2 are listed in Table 4.1. The mean methane concentration on LGS was low (0.6%). In most field measurements, its concentrations on LGS were below the detection limit of the methane detector (0.5%). However, soil in LGS was not always free of methane; a maximum concentration of 10% was detected. Its mean concentration on HGS (16.1%) was significantly higher than on LGS ($P<0.001$). The maximum concentration on HGS soil was 41.0% and the minimum concentration was 1.7%. The mean methane concentration on HGS was 17 times higher than the mean methane concentration on LGS.

Only trace concentrations of CO_2 (mean = 0.7 %) were detected on LGS. As in the case of methane, the CO_2 concentrations on LGS

Table 4.1 Means of soil gas concentrations on GDB sites during the project period. [all units are in %, vol. vol.$^{-1}$; #: gas samples measured on 20/9/89, 17/12/88, 31/3/88 and 25/8/89; a,b: distinct classes between the HGS and LGS, according to the Student's t test (P<0.01); ND: not detectable]

Site		Methane	CO_2	O_2
LGS	$\bar{x}$#	0.9a	0.7a	19.3a
	SD	2.9	1.4	2.0
	Min.	ND	ND	19.0
	Max.	10.0	4.7	20.3
HGS	$\bar{x}$	16.1b	17.6b	9.7b
	SD	13.5	11.7	9.2
	Min.	1.7	2.0	1.6
	Max.	41.0	39.0	16.3

were below the 0.1% lower detection limit in most field measurements. The mean concentration of CO_2 in HGS soil was 17.6%, close to the mean concentration of methane (16.1%). A significant difference ($P<0.001$) in CO_2 concentration was found between the LGS and HGS.

The concentration of O_2 in LGS soil was high. The mean O_2 concentration for the project period was 19.3%, close to the ambient air O_2 concentration of 20.9%. The O_2 concentration in LGS soil did not fluctuate much, the SD was 2.0%. The mean O_2 concentration detected in HGS soil was 9.7%, the minimum concentration was 1.6% and the maximum concentration was 16.3%. The O_2 concentration in HGS soil was unstable, the SD was 9.2%. Significant difference in O_2 concentration was found between the LGS and HGS ($P<0.01$), and even the minimum O_2 concentration found on LGS (19.0) was higher than the maximum O_2 concentration found on HGS (16.3).

Figure 4.1 shows the seasonal variations in the concentration of methane, CO_2 and O_2 on the GDB sites. The methane concentration on the study sites was significantly and positively correlated with the air temperature, while the O_2 level was negatively correlated with the air temperature. Moreover, the O_2 concentration was inversely proportional to the concentration of methane and CO_2. Soil landfill gas concentration was not correlated with rainfall (Table 4.2).

A strong odour of landfill gas was detected on the HGS during the study period. It was "sweet" and acrid. The odour on a hot summer day was much stronger than in winter. LGS did not have an odour problem at any time during the whole project period.

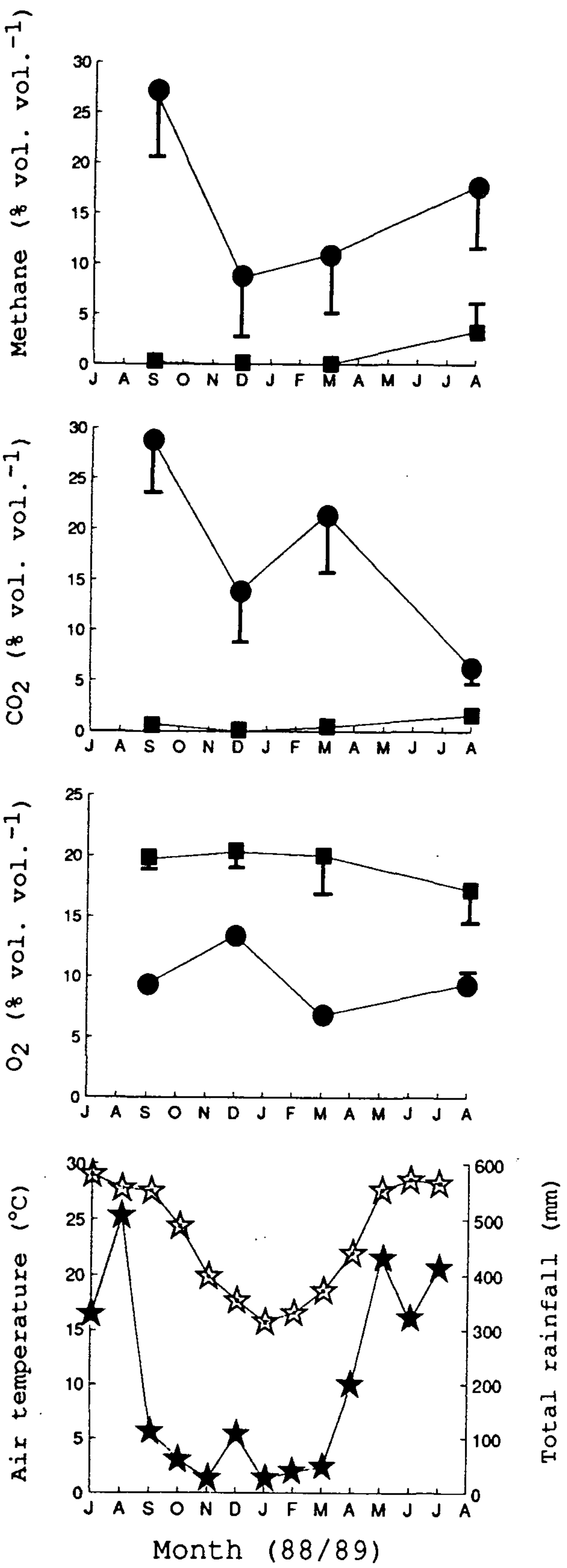


Fig. 4.1 Soil landfill gas concentrations on the LGS (■) and HGS (●) in GDB landfill, compared with air temperature (☆) and total rainfall (★) (see Section 4.1).

Table 4.2 Correlation among landfill gas components on GDB sites, and air temperature and total rainfall. [Significant level *P<0.05, **P<0.01]

	Air temperature	Total rainfall	Methane	CO_2
Methane	0.800**	0.180		
CO_2	-0.134	-0.799	0.799*	
O_2	-0.470	0.240	-0.785*	-0.780*

4.2 Relative viability of the plants

Two hundred seedlings belonging to 10 species of tree were transplanted to the LGS and HGS. All seedlings were successfully transplanted. No one stand died within the first week. Although all seedlings were transplanted successfully to the sites and could withstand the landfill conditions for at least one week, seedlings of some species had high mortality rates within the first month (Fig. 4.2).

Among the seedlings of the 10 species grown on LGS, the mortality rate of Machilus breviflora was the highest. 70% of M. breviflora seedlings died before the end of the project. In fact, 50% of M. breviflora seedlings died within four months. The mortality rate of Castanopsis fissa was the second highest on LGS. 60% of C. fissa seedlings died within the project period. 10% of Liquidambar formosana seedlings died in the second month of growth on LGS, and no L. formosana seedling died in the following months. Zero percent death was recorded for seven species: Acacia confusa, Albizzia lebbek, Aporusa chinensis, Bombax malabaricum, Litsea glutinosa, Pinus elliottii, Tristania conferta.

On the HGS at least 10% of seedlings of each species died within the project period. Trees were classified into three classes with respect to their mortality rate, Aporusa chinensis, Castanopsis fissa, Liquidambar formosana, Litsea glutinosa and Machilus breviflora had high mortality rates. More than 50% of each of the above five species died within the project period. Castanopsis fissa was the only species having 100% mortality

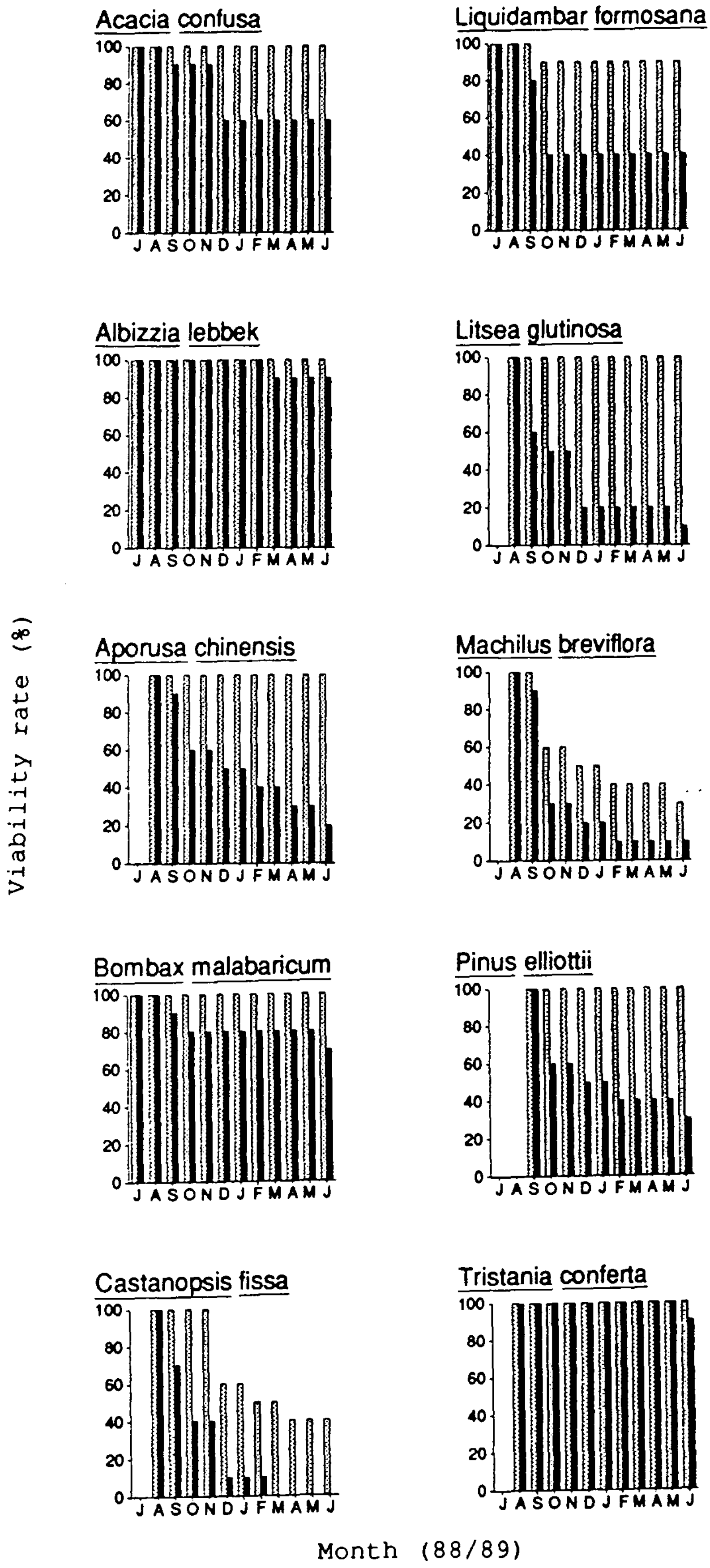


Fig. 4.2 Monthly viability rate of the 10 species on the LGS (▭) and HGS (▬) in GDB landfill (see Section 4.2).

rate. 90% of *Castanopsis fissa* seedlings died within the first 4 months and all died within the first 7 months. *Acacia confusa*, *Bombax malabaricum* and *Pinus elliottii* belonged to the group with moderate mortality rate, between 30 to 40%. *Albizzia lebbek* and *Tristania conferta* had the lowest mortality rate, 90% of their seedlings surviving after 10 to 11 months.

4.3 Relative growth of surviving plants

The mean heights of viable seedling after 10 to 11 months of growth on LGS and HGS are compared in Table 4.3. For all 10 species, their mean heights on LGS were taller than the mean heights on HGS, and five species showed significant difference between the sites.

The average heights of viable seedlings at the end of the period are compared with their original average heights transplanted to GDB sites (Table 4.4). The growth rates of *Acacia confusa* and *Tristania conferta* seedlings were the highest, their average heights increased by 262% and 243%, respectively on LGS, and 108% and 89%, respectively on HGS. Trees with a moderate growth rate were *Albizzia lebbek*, *Bombax malabaricum*, *Liquidambar formosana* and *Pinus elliottii*. Seedling of these four species increased in average height by 100% - 200% on LGS and 25% - 33% on HGS. The growth of seedlings of all the 10 species on HGS was slower than of seedlings on LGS. *Aporusa chinensis*, *Castanopsis fissa*, *Litsea glutinosa* and *Machilus breviflora* were slow growers. Their height increased less than 100% on LGS. On HGS, the average heights of *Litsea glutinosa* and *Machilus breviflora*

Table 4.3 Growth characteristics of viable seedlings on GDB sites after 10 to 11 months of growth. [Distinct classes between LGS and HGS, according to Student's t test: *P<0.05, *P<0.01, ***P<0.001; NC: not counted; -: not calculated, sample size ≤ 2]

Species	Plant height (cm)				Base diameter [mm]			
	LGS		HGS		LGS		HSG	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Acacia confusa	75.3	28.2	48.3	29.0	9.9	3.3	6.1	3.4
Albizzia lebbek	74.3**	16.5	44.0	25.5	12.8	2.9	7.2	4.8
Aporusa chinensis	38.5	7.7	28.0	2.8	5.4	3.0	4.3	0.6
Bombax malabaricum	47.9***	11.2	18.7	6.0	10.0**	2.2	4.3	0.3
Castanopsis fissa	26.0	18.6	D	-	6.4	0.8	6.0	NC
Liquidambar formosana	40.8**	11.4	20.8	5.0	7.3	1.8	3.9	0.9
Litsea glutinosa	23.5	8.7	13	-	7.9**	0.9	4.6	0.1
Machilus breviflora	32.7	6.8	16	-	6.9	2.0	NC	NC
Pinus elliottii	35.1*	7.9	20.8	1.7	7.8*	2.2	4.4	0.6
Tristania conferta	86.4***	9.0	47.7	21.9	8.9***	1.0	4.2	1.0

Species	Number of leaves				Leaf area [cm^2]			
	LGS		HGS		LGS		HSG	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Acacia confusa	129.7	129.3	38.5	31.7	7.9	1.1	6.3	1.4
Albizzia lebbek	8.5***	2.4	3.4	0.92	3.2**	0.5	1.3	0.9
Aporusa chinensis	28.7*	8.6	12.0	8.5	26.5*	10.1	10.1	2.6
Bombax malabaricum	6.2***	1.3	2.7	0.52	47.6*	22.5	6.2	2.4
Castanopsis fissa	11.0	9.9	D	-	61.2*	49.3	NC	-
Liquidambar formosana	63.9*	31.3	25.0	12.9	30.5	21.4	3.2	2.0
Litsea glutinosa	12.6	8.1	8	-	26.1**	5.2	6.5	0.6
Machilus breviflora	59.0	32.1	19	-	11.2	2.8	NC	-
Pinus elliottii	NC		NC		NC	-	NC	-
Tristania conferta	80.1***	23.6	31.1	26.6	55.8**	19.3	16.5	4.7

Table 4.4 Increase (%) in average height and average number of leaves of viable seedlings on GDB sites. [D: all seedlings died within the study period; NC: not counted]

Species	% increase in comparison with the original height		% increase in comparison with the original number of leaves	
	LGS	HGS	LGS	HGS
Acacia confusa	262	108	875	166
Albizzia lebbek	133	33	98	6
Aporusa chinensis	96	33	104	-28
Bombax malabaricum	174	9	24	-38
Castanopsis fissa	95	D	17	D
Liquidambar formosana	161	31	618	181
Litsea glutinosa	44	-16	-7	-39
Machilus breviflora	47	-27	61	-44
Pinus elliottii	108	25	NC	NC
Tristania conferta	243	89	531	115

seedlings became shorter than their original heights, because the survival rates of their short transplants were higher.

At the end of the project period, the average base diameters of viable seedlings on LGS were compared with seedlings on HGS (Table 4.3). For all the 10 species, base diameters of seedlings on HGS were smaller than seedlings on LGS. Seedlings of Tristania conferta showed a significant difference ($P<0.01$).

The average number of leaves of viable seedlings after about a year of growth on LGS and HGS are compared in Table 4.3. The number of leaves of Castanopsis fissa, Litsea glutinosa, Machilus breviflora and Pinus elliottii were not compared due to there being insufficient viable replicates. Acacia confusa was the only species showed no significant difference in number of leaves after the study period. Other five species showed significant differences at different significant levels.

The average number of leaves of the 10 species at the end of the project period is compared with the original average number of leaves transplanted to GDB sites (Table 4.4). Acacia confusa seedlings increased by 875% and 166% on LGS and HGS, respectively. Liquidambar formosana was a fast-growing deciduous tree. After the winter, its number of leaves increased rapidly and there were soon more leaves than before being transplanted to the GDB sites. Tristania conferta was the third fastest growing tree in terms of number of leaves, showing a 531% increase on LGS. For the other seven species, their average numbers of leaves showed less changes compared with the original numbers.

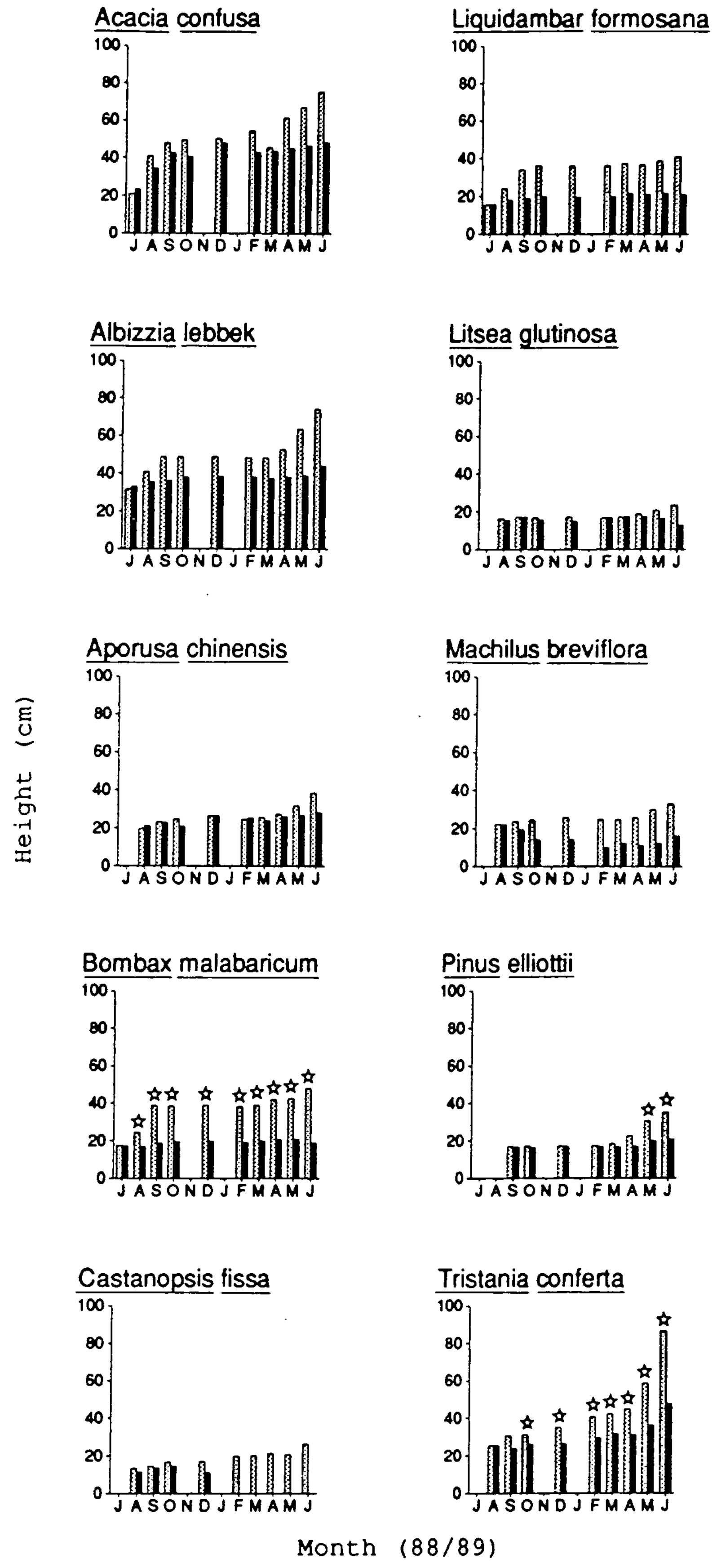


Fig. 4.3. Monthly changes in height of seedlings on LGS (▨) and HGS (■) in GDB landfill (see Section 4.3). (Distinct classes between LGS and HGS, according to Students' t test, P<0.001)

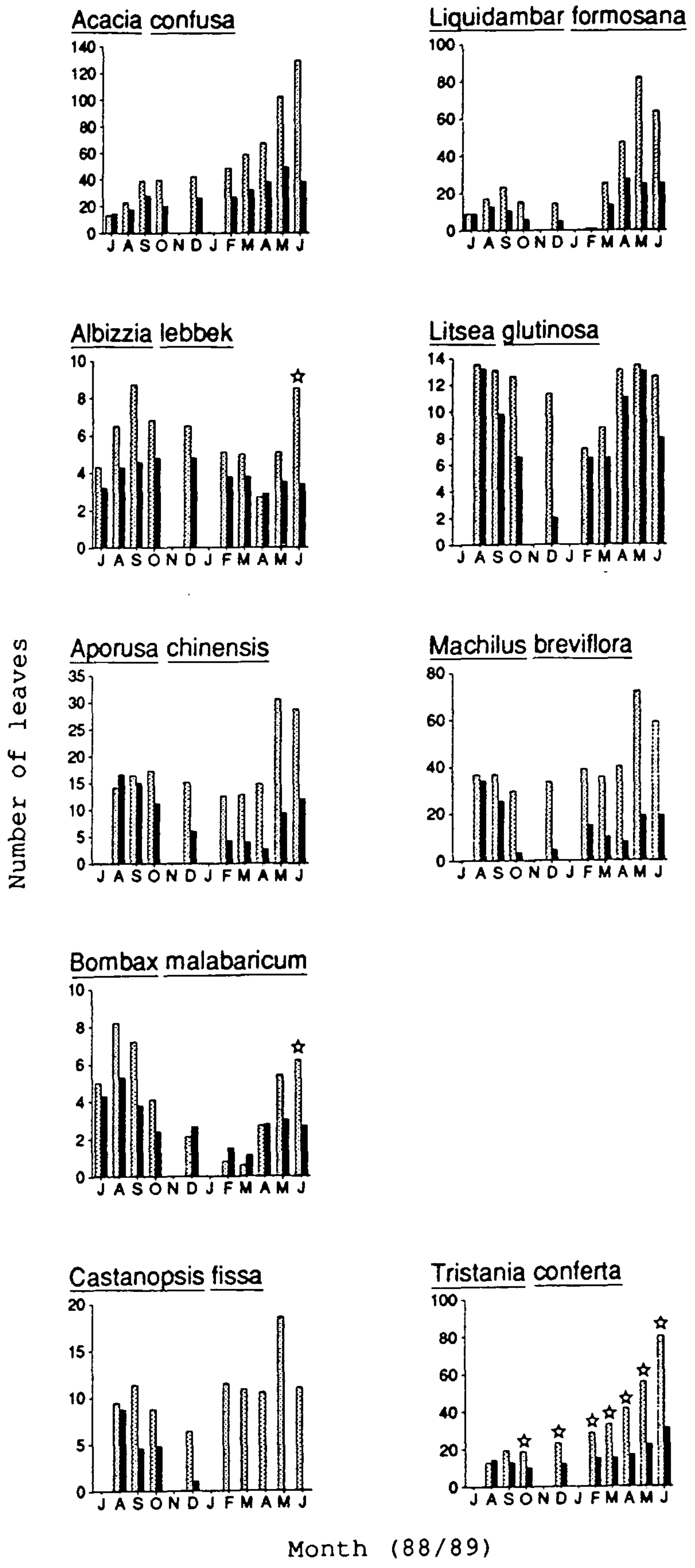


Fig. 4.4. Monthly changes in number of leaves of seedlings on LGS (▨) and HGS (■) in GDB landfill (see Section 4.3). (Distinct classes between LGS and HGS, according to Students' t test, P<0.001)

The stomatal resistances of the 10 species on GDB sites were measured on a sunny day on November 1988 (Table 4.5). The stomatal resistances of Acacia confusa, Albizzia lebbek and Liquidambar formosana seedlings grown on LGS were higher than those grown on HGS. For the other 7 species, the stomatal resistances of seedlings grew on LGS was lower than those grew on HGS. Among the 10 species, Castanopsis fissa was the only species having a significant difference between the two sites.

For all the 10 species, the general performance of seedlings on HGS was inferior than seedlings on LGS. Fig. 4.5.A to 4.5.J are photographs taken on GDB sites and the morphological differences of the seedlings are shown. Photographs were taken mostly at the end of the project and some were taken shortly after the seedlings had been transplanted to the sites. General morphological changes and symptoms developed on the HGS seedlings with respect to LGS seedlings were that leaves became xeromorphic, brown in colour, chlorophyll deficient and brittle in texture.

Insects damaged parts of the leaves of Albizzia lebbek, Castanopsis fissa and Machilus breviflora. Castanopsis fissa was susceptible to insect bites, up to 30% of its leaves was bitten at least once by insect. Insect funnel was observed on some leaves of Machilus breviflora and their damage was very minor. As a whole, insects did not cause lethal damage to any seedling.

Most of the M. breviflora seedlings were infected with fungal disease a few weeks after they had been transplanted to the GDB sites. Fungicide was sprayed on the plants. Seedlings on LGS soon recovered. However, the disease on HGS seedlings could hardly be controlled. Leaves of those infected seedlings became

Table 4.5 Stomatal resistance [S cm^{-1}] of seedlings in November 1988. Distinct classes between the LGS and HGS, according to Student's t test: *$P<0.05$; - not measured]

Species	LGS		HGS		$\frac{\bar{x} \text{ of HGS}}{\bar{x} \text{ of LGS}} \times 100\%$
	$\bar{x}$	SD	$\bar{x}$	SD	
Acacia confusa	25.9	10.5	20.9	14.2	86
Albizzia lebbek	12.8	5.7	8.6	7.5	67
Aporusa chinensis	5.3	2.4	6.9	4.6	127
Bombax malabaricum	16.2	8.6	17.3	15.1	93
Castanopsis fissa	4.3*	1.6	6.8	0.1	178
Liquidambar formosana	15.6	6.5	9.6	8.8	58
Litsea glutinosa	4.1	5.1	10.6	6.7	249
Machilus breviflora	5.2	1.6	7.5	7.1	145
Pinus elliottii	-		-		-
Tristania conferta	3.5	2.5	5.2	2.9	168

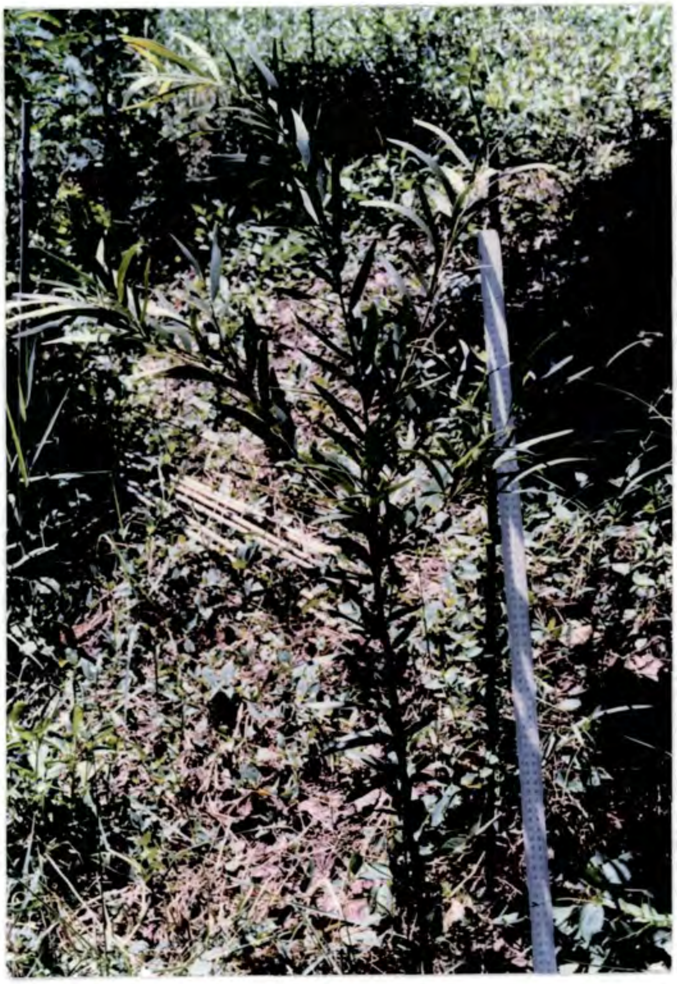


Fig. 4.5.A Acacia confusa after about a year of growth on Gin Drinkers' Bay (GDB) landfill (see Section 4.3). The rule is 1 m long.

a. A healthy stand on the low-gas-site (LGS).

b. Healthy leaves of (a).

c. A viable stand on the high-gas-site (HGS).

d. Leaf browning was a typical physiological symptom of HGS grown seedlings

Fig. 4.5.B Albizzia lebbek after about a year of growth on GDB landfill (see Section 4.3).

a. A healthy young tree on the LGS.

b. Healthy compound leaves on the LGS with some yellow leaflets. This species tends to shed its leaflets continuously throughout the year.

c. Poor seedling growth on the HGS.

d. Chlorotic A. Lebbek leaf found on the HGS.

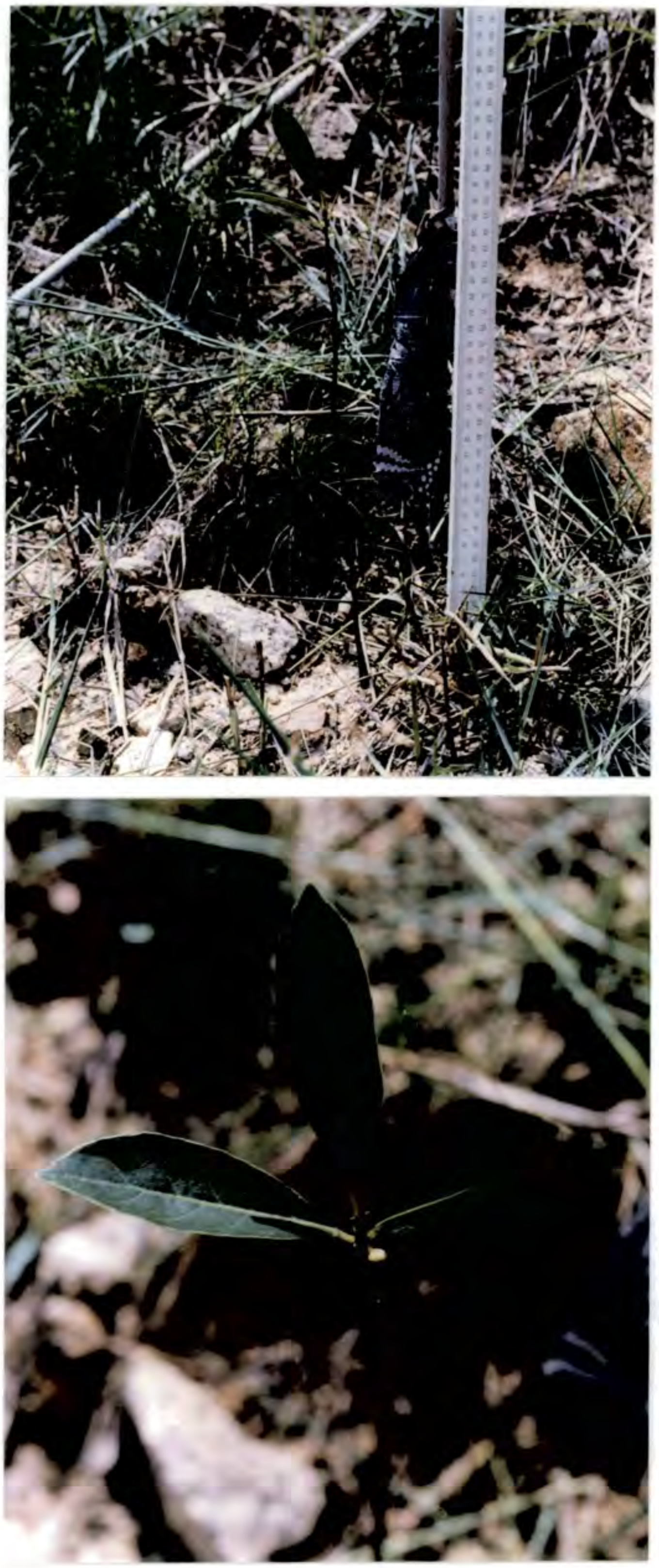


Fig. 4.5.C Aporusa chinensis after about a year of growth on GDB landfill (see Section 4.3).

a. A healthy young seedling on the LGS. This species was a slow-grower and attained a height of only 20 cm.

b. Mesophytic leaves on the LGS.

c. The only surviving seedling on the HGS.

d. Three xeromorphic leaves from (c).

Fig. 4.5.D <u>Bombax</u> <u>malabaricum</u> after about a year of growth on GDB landfill (see Section 4.3).

a. A healthy seedling on the LGS.

b. Mature 5-lobed leaves on the LGS.

c. A miniature seedling on the HGS.

d. Small juvenile 3-lobed leaves on the HGS.

Fig. 4.5.E Growth of *Castanopsis fissa* seedlings on GDB landfill (see Section 4.3).

a. A healthy seedling on the LGS, after about a year of growth.

b. A dead seedling on the HGS (see Section 4.2).

LFFC

Fig. 4.5.F Growth of Liquidambar formosana seedlings on GDB landfill (see Section 4.3).

a. A healthy seedling on the LGS at the end of the project period.

b. A young seedling with deep green leaves, shortly after transplantation to the LGS.

c. Yellowing was a common symptom on LGS seedlings.

d. A miniature seedling with brown leaves on the HGS.

Fig. 4.5.G. Litsea glutinosa after about a year of growth on GDB landfill (see Section 4.3).

a. A healthy seedling on the LGS.

b. A seedling on the HGS. Compared with leaves from the LGS, those on the HGS were short and more waxy.

Fig. 4.5.H. <u>Machilus</u> <u>breviflora</u> after about a year of growth on GDB landfill (see Section 4.3).

a. A seedling infected by a fungal disease during first month of growth on the LGS.

b. HGS seedling death, due to a fungal infection.

Fig. 4.5.I. Pinus elliottii after about a year of growth on GDB landfill (see Section 4.3).

a. A healthy stand on the LGS.

b. A close-up view of (a). Control plants exhibit larger leaves internode than those from the HGS.

c & d. Seedlings on HGS.

Fig. 4.5.J. Tristania conferta after about a year of growth on GDB landfill (see Section 4.3).

a. A seedling exceeded 1 m in height on LGS.

b. A close-up of (a), showing the morphology of healthy leaves.

c & d. Of all species, (Figs 4.5.A to 4.5.I), only T. conferta exhibit healthy growth on the HGS.

red in colour (Fig. 4.5.H) and 70% of seedlings on HGS died within the first two months. However, although all seedlings on the LGS recovered from the fungal disease, their mortality rate was high in the first two months. At the end of the project, only three M. breviflora seedlings survived on the LGS and the remaining seedling on HGS was dying.

Students' t test was used to evaluate four growth variables between seedlings grown on LGS and HGS. These four growth variables are height, base diameter, number of leaves and leaf size (Table 4.6). The test was not applicable to Castanopsis fissa, as all seedlings on HGS died within the project period. The average Students' t value of each species was calculated and ranked by descending order. Acacia confusa has the least negative t value; other species in the descending order are: Aporusa chinensis, Liquidambar formosana, Litsea glutinosa, Albizzia lebbek, Pinus elliottii, Bombax malabaricum, Tristania conferta.

4.4 Summary

High landfill gas concentration was detected on the HGS soil but only trace concentration on the LGS. The landfill gas concentration in GDB sites was correlated with air temperature. On the LGS and HGS, high mortality rates were found for Machilus breviflora and Castanopsis fissa seedlings. The mortality rates of Acacia confusa, Bombax malabaricum and Tristania conferta seedlings were low. Rapid growth in term of height, base diameter, number of leaves and leaf area were observed on Acacia confusa and Tristania conferta seedlings. In comparing the above

Table 4.6 Growth characteristics of viable seedlings on HGS as percent of value of seedlings on LGS. [Distinct classes between the LGS and HGS, according to Students' t test: *$P<0.05$, **$P<0.01$, ***$P<0.001$; D: All replicates on HGS died within the study period; NC: Not counted, leaves of *Pinus elliottii* are too numerous and leaf size is too small for the porometer, not enough healthy leaves in *Machilus breviflora*; #: Sample size is 1]

Species	Growth as percent of control			
	Plant height	Base diameter	No. of leaves	Leaf size
Acacia confusa	64	62	30	79
Albizzia lebbek	59**	56	40***	42**
Aporusa chinensis	73	81	42*	38*
Bombax malabaricum	39***	43**	43***	13*
Castanopsis fissa	D	D	D	D
Liquidambar formosana	51**	54	39*	11*
Litsea glutinosa	55	58**	63	25**
Machilus breviflora	49#	80#	32#	NC
Pinus elliottii	59***	56*	NC	NC
Tristania conferta	55***	47***	39***	30**

four growth parameters between seedlings grew on LGS and HGS, Acacia confusa seedlings showed least significant different while Tristania conferta seedling showed the largest significant different.

CHAPTER 5

LABORATORY STUDIES ON INFLUENCE OF LANDFILL GAS

The field studies (Chapter 4) demonstrated there was a strong correlation between landfill gas concentration in soil and adverse tree growth. A controlled laboratory experiment was performed to investigate how landfill gas affects tree growth.

5.1 Soil gaseous composition of study tanks

The root portions of the 10 species (Table 2.1) were fumigated by simulated landfill gas. The gas was produced by anaerobic digesters and fed into the study tanks (Section 2.2). Steady gas production at about 20 - 30 l d^{-1} was achieved after one week. Fig. 5.1 shows the daily gas production rate and the gaseous composition in the first 2 months. The ratio between methane and carbon dioxide in the gas was approximately 60% : 40% (by volume). No detectable ammonia and ethylene were found (≤0.1 µl l^{-1}).

In the control tanks, the mean daily CO_2 concentrations within the six-week study period were in the range 0.18% - 0.72%. The mean O_2 concentrations were 20.2% - 20.5%, indicating a 0.7% - 0.4% O_2 depletion. Ethylene was below the detection limit (≤0.1 µl l^{-1}).

For the gas treatment, the simulated landfill gas feed in rate was 32.3 to 43.8 l d^{-1} (Table 5.1), and the resultant average methane, CO_2 and O_2 concentrations in the tank soils were 16.9%, 20.2% and 8.7%, respectively. These concentrations were adjusted

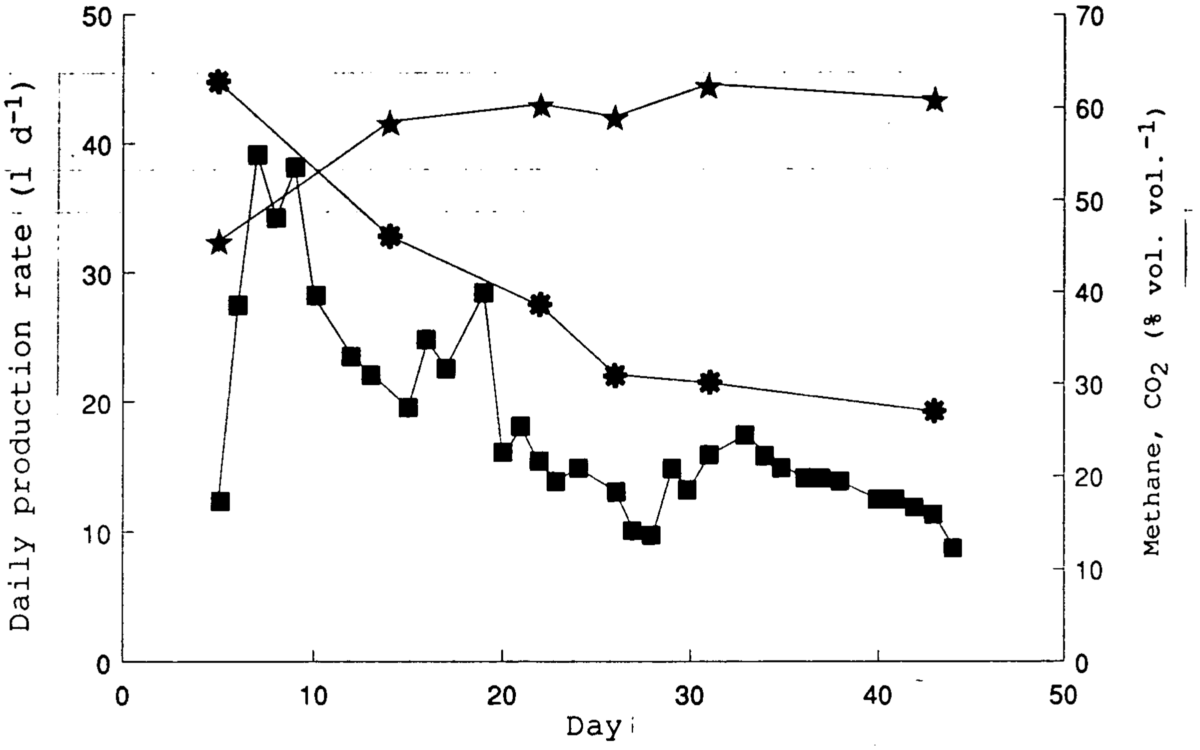


Fig. 5.1 45-day digester gas production rate (■) and compostion of the gas. (★ methane, ✱ CO$_2$)

Table 5.1 Simulated landfill gas fed in rate and soil gaseous composition of study tanks.

Species	Simulated landfill gas fed in rate [l d^{-1}]		Control tank				Fumigation tank					
			CO_2 [%]		O_2 [%]		Methane [%]		CO_2 [%]		O_2 [%]	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Acacia confusa	33.10	11.69	0.43	0.19	20.6	0.13	18.86	6.02	13.63	4.30	14.1	1.6
Albizzia lebbek	43.07	16.26	0.32	0.06	20.6	0.11	15.36	4.76	16.29	4.43	13.7	2.2
Aporusa chinensis	38.72	8.46	0.18	0.02	20.6	0.10	14.84	2.98	12.15	3.07	14.6	1.7
Bombax malabaricum	32.24	7.02	0.72	0.27	20.2	0.17	16.76	2.67	31.53	7.76	0.5	0.9
Castanopsis fissa	36.95	13.28	0.37	0.13	20.5	0.12	21.84	7.64	33.08	6.20	0.9	2.8
Liquidambar formosana	35.72	9.71	0.49	0.21	20.4	0.16	17.47	3.31	26.70	7.98	5.2	3.1
Litsea glutinosa	43.83	18.46	0.30	0.05	20.5	0.16	21.81	2.71	20.04	2.79	8.4	2.4
Machilus breviflora	40.58	7.80	0.22	0.05	20.5	0.18	10.08	4.74	18.26	3.80	3.7	4.9
Pinus elliottii	40.49	8.70	0.19	0.03	20.6	0.09	15.01	4.73	11.43	3.24	13.6	3.0
Tristania conferta	38.47	8.03	0.24	0.07	20.5	0.07	17.60	5.21	18.39	5.29	8.1	2.6
$\bar{x}$:	38.32		0.35		20.5		16.96		20.15		8.7	
SD :	3.88		0.17		3.5		3.49		7.77		0.5	
maximum:	43.83		0.72		20.6		21.84		33.08		14.6	
minimum:	32.24		0.18		20.2		10.08		11.43		0.5	

to simulate the soil landfill gas concentration on the high-gas-site (HGS) in Gin Drinkers' Bay (GDB) landfill (Table 4.1).

The gaseous compositions in the treatment tanks varied greatly among species. The range of methane concentrations was 14.8% to 21.8%. Although the feed in gas rates were similar for all tanks, the CO_2 concentrations ranged from 11.4% to 33.1%. Extremely low O_2 concentrations (<0.5%) were found in the tanks of Bombax malabaricum and Castanopsis fissa.

Although the ratio between methane and CO_2 concentrations in the simulated gas was fixed at 60% : 40% (by volume), the ratio of these two gases varied in the tanks. The methane concentration was 1.5 times higher than the CO_2 concentration in Acacia confusa and Pinus elliottii. However, the methane concentrations in Bombax malabaricum, Castanopsis fissa, Liquidambar fissa and Machilus breviflora were much lower than the CO_2 concentrations, indicating a net uptake of methane and/or net production of CO_2.

5.2 Effects of simulated landfill gas on plants

High tree mortality rate was demonstrated on GDB sites in the first two months. In contrast, seedlings in the laboratory studies, fumigated with similar concentrations of gases, had a 100% viability after the six-week laboratory study period. However, during that six-week period, the gas exerted different effects on the plants and differences in growth and symptoms were observed.

The mean heights and numbers of leaves of the 10 species after treatment were compared with their control groups. Bombax malabaricum and Liquidambar formosana showed significant differences in height, $P<0.05$ and $P<0.001$, respectively. In terms of the number of leaves, only Liquidambar formosana and Tristania conferta showed significant differences after treatment ($P<0.01$). Although the average number of T. conferta leaves decreased 5% after treatment. Its new leaves formed continuously during the treatment; its rate of leaf shedding was higher than the leaf forming rate and caused the decrease in the average number of leaves.

The final average heights and number of leaves in the control treatment were compared with their original figures to study the relative growth rate of plants (Table 5.2). Except for Pinus elliottii leaves which were not counted and not applicable to comparison, the growth rates of each species were similar in terms of height and number of leaves. The growth rates of Acacia confusa, Liquidambar formosana and Tristania conferta were the highest, increasing by more than 50%. The growth rate of Albizzia lebbek, Bombax malabaricum, Castanopsis fissa, Litsea glutinosa and Machilus breviflora were medium, increasing 10% - 50%. Aporusa chinensis and Pinus elliottii were slow-growers, increasing less than 10%.

Figs 5.4.A to 5.4.J show the morphology of seedlings after gas treatment, and the control seedlings. For the above-ground parts, no observable abnormality was found on Aporusa chinensis, Castanopsis fissa and Pinus elliottii seedlings after the treatment; seedlings looked the same as when they were being transplanted. Throughout the six-week period, Acacia confusa and Albizzia lebbek showed rapid healthy growth and no adverse effects after treatment were found. Three out of 10 Acacia

Table 5.2 Growth characteristics of seedlings after the 6-week simulated landfill gas fumigation [mean of 10 replicates; NC: not counted; distinct classes according to Students' t test: *P<0.05, **P<0.01, ***P<0.001].

Species	Height(cm)				Mean No. of leaf			
	Control		Fumigation		Control		Fumigation	
	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Acacia confusa	36.4	6.7	35.7	6.9	21.3	3.4	23.0	7.4
Albizzia lebbek	29.7	8.4	33.3	12.2	5.0	2.3	5.7	2.7
Aporusa chinensis	21.0	2.6	21.3	2.7	12.5	4.0	13.2	2.7
Bombax malabaricum	20.8*	4.9	17.0	2.1	6.0	1.7	5.2	1.1
Castanopsis fissa	9.5	1.7	9.7	1.7	11.4	2.9	9.9	2.2
Liquidambar formosana	24.4***	5.6	15.6	2.4	14.7**	2.6	11.4	1.8
Litsea glutinosa	21.2	2.5	23.9	6.6	15.4	2.4	14.2	4.2
Machilus breviflora	20.9	4.8	20.1	6.1	45.6	18.5	33.2	18.1
Pinus elliottii	18.3	3.1	16.0	2.5	ND		ND	
Tristania conferta	28.6	5.4	22.4	2.1	19.5**	6.6	13.3	2.5

Species	% increase in compare with the original height		% increase in compare with the original number of leaves	
	Control	Fumigation	Control	Fumigation
Acacia confusa	77	70	103	117
Albizzia lebbek	29	48	35	84
Aporusa chinensis	5	13	4	9
Bombax malabaricum	44	25	28	30
Castanopsis fissa	12	19	37	8
Liquidambar formosana	128	41	133	93
Litsea glutinosa	43	70	28	33
Machilus breviflora	40	21	25	1
Pinus elliottii	7	1	NC	NC
Tristania conferta	55	14	60	-5

Fig. 5.2.A *Acacia confusa* treated with simulated landfill gas (see Section 5.2). (The rule is graduated in cm)

a. Gas treatment seedlings (left) compared with control plant (right).

b. Control plant roots.

c. Gas treatment plant roots. Note that tap root growth was not affected.


40
Fumigation


Acacia confusa
(Acacia)
台灣相思
6 Weeks
Control


Fumigation
Acacia confusa
(Acacia)
台灣相思
6 Weeks

Fig. 5.2.B *Albizzia lebbek* treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Control plant roots.

c. Gas treatment roots. Note that tap root growth was not affected.


Albizia lebbek
(Lebbek Tree)
大葉合歡
6 Weeks


Albizia lebbek
(Lebbek Tree)
大葉合歡
6 Weeks

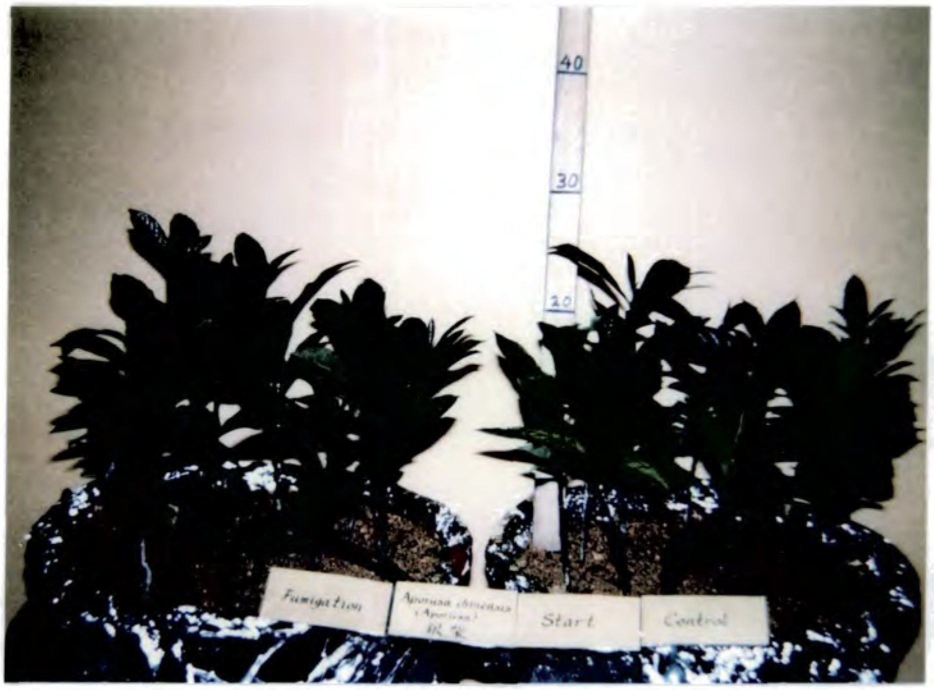

Fumigation
Albizia lebbek
(Lebbek Tree)
大葉合歡
6 Weeks

Fig. 5.2.C *Aporusa chinensis* treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Control plant roots. Note the dense tap root system.

c. After gas treatment, tap root growth was suppressed.


40
30
20
Fumigation
Aporusa chinensis
(Aporusa)
銀柴
Start
Control


Aporusa chinensis
(Aporusa)
銀柴
6 Weeks
Control


cm
-5
-10
-15
-20
-25
cm
Fumigation
Aporusa chinensis
(Aporusa)
銀柴
6 Weeks

Fig. 5.2.D *Bombax malabaricum* treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Clorotic leaf after the gas treatment.

c. After gas treatment, old root in deep soil rotted and a shallow root system formed.


Fumigation
Bombax malabaricum (Tree cotton) 木棉
6 Weeks
Control


6 Weeks
Bombax malabaricum (Tree cotton) 木棉
Fumigation

Fig. 5.2.E <u>Castanopsis</u> <u>fissa</u> treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Apical root growth was suppressed after the gas treatment.

Fig. 5.2.F Liquidambar formosana treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right). Note the stunted growth of seedlings after the gas treatment.

b. Control plant roots.

c. The gas treatment suppressed the apical root growth but induced the adventitious root growth.


40
30
Fumigation
Liquidambar formosana
(Sweet Gum)
楓樹
6 Weeks
Control


cm
-5
-10
-15
-20
-25
cm
6 Weeks
Control


cm
-5
-10
-15
-20
Fumigation
Liquidambar formosana
(Sweet Gum)
楓樹
6 Weeks

Fig. 5.2.F (continue).

d. Healthy _Liquidambar formosana_ control plants

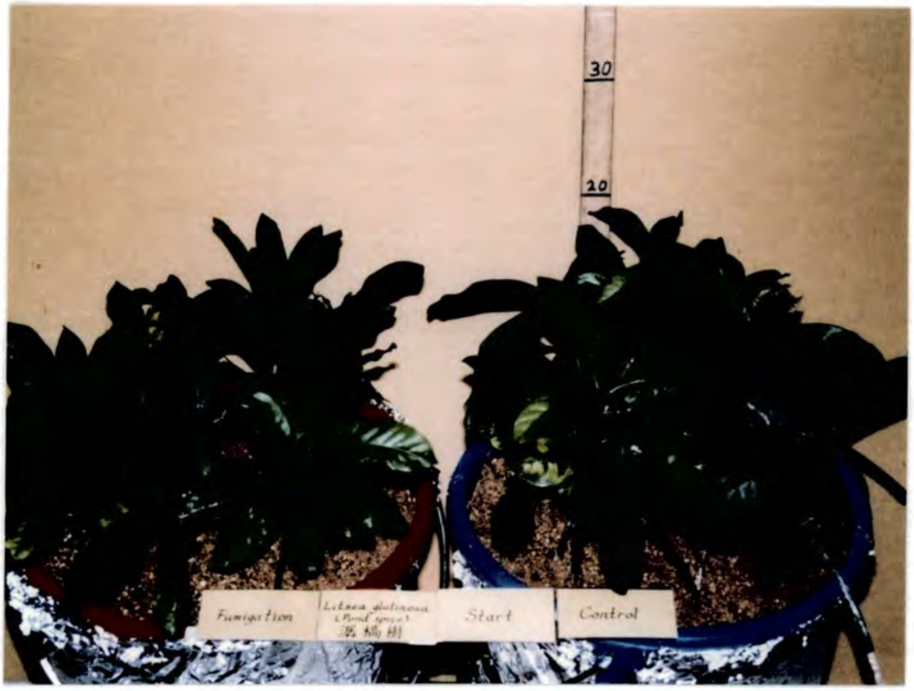
e. Chlorotic leaves after gas treatment.

Fig. 5.2.G Litsea glutinosa treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Control plant roots. Note that the growth rate of this species was slow, new roots formed within the 6-week period were rare.

c. Roots after the gas treatment, some of the old roots in deep soil died.


30
20
Fumigation
Litsea glutinosa
(Pond spice)
潺槁樹
Start
Control


Litsea glutinosa
(Pond spice)
潺槁樹
6 Weeks
Control


cm
5
10
15
20
25
Fumigation
Litsea glutinosa
(Pond spice)
潺槁樹
6 Weeks

Fig. 5.2.H *Machilus* *breviflora* treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Control plant roots.

c. Adventitious root growth was stimulated after the gas treatment.


40
30
20
Fumigation
Machilus breviflora
(Short-flowered Machilus)
短花楠
Start
Control


6 Weeks
Machilus breviflora
(Short-flowered Machilus)
短花楠
Control


Fumigation
6 Weeks
Machilus breviflora
(Short-flowered Machilus)
短花楠

Fig. 5.2.I *Pinus elliottii* treated with simulated landfill gas (see Section 5.2).

a. Gas treatment seedlings (left) compared with control plant (right).

b. Normal control plant roots.

c. Apical root growth was hindered after the gas treatment.


40
30
Fumigation
Pinus elliottu
(Slash pine)
湿地松
Start
Control


cm
-5
-10
-15
-20
-25
cm
Pinus elliottu
(Slash pine)
6 Weeks.
Control


cm
-5
-10
-15
-20
-25

Fig. 5.2.J <u>Tristania</u> <u>conferta</u> after the gas influence study (see Section 5.2)

a. Shoot growth was suppressed after the gas treatment (left), compared with the control (right).

b. After gas treatment, apical root growth was suppressed, but adventitious root growth was stimulated.

d. Chlorosis of leaves after gas treatment.


40
30
Fumigation
Tristania conferta
(Brush box)
紅膠木
6 Weeks
Control


cm
-5
-10
-15
-20
-25
cm


eks
Fumigation
Tristania conferta
(Brush box)
紅膠木

confusa replicates in both the treatment and control tanks formed lateral branches within the six-week period. Bombax malabaricum showed stunted growth after treatment; new leaves were three-lobed, juvenile and chlorotic; new leaves in the control tanks were five-lobed and mature. Stunted growth was also observed in Liquidambar formosana. Its new leaves were pink-green or white. Slightly etiolated growth was observed in Litsea glutinosa and Machilus breviflora seedlings in both the fumigation and control treatments. For Tristania conferta, the average height, number of leaves and leaf size were reduced after treatment.

After the six-week study period, all seedlings were harvested for dry weight analysis and root growth patterns were observed. Generally, roots in control tanks grew downward and most had young roots penetrating the gravel layer at the tank bottom. Roots in treatment tanks, under the influence of landfill gas, showed restricted growth in the upper soil of tanks and formed a horizontal root system. For example, dense Castanopsis fissa roots were noted in the 2-cm top soil layer after treatment; most deep roots became necrotic and died. Root growth of Liquidambar formosana ceased after treatment; very few roots grew outwards into the tank soil from the intact transplantation soil core. The roots of Pinus elliottii grew upwards after treatment. The roots of Albizzia lebbek, Aporusa chinensis, Bombax malabaricum, Litsea glutinosa, Machilus malabaricum and Tristania conferta grew horizontally under the influence of the gas. Surprisingly, roots of Acacia confusa in the fumigation tank penetrated into the gravel layer where the atmosphere was merely pure simulated landfill gas. Its young roots in the fumigation tank had a similar magnitude of root hair as the control, and the old roots were coated with some white flaky substances. A. confusa was the only species tested with roots that kept growing downwards under continuous simulated landfill gas fumigation.

Tap root growth, with respect to maximum root length, was commonly suppressed after treatment (Table 5.3). Only seedlings of A. confusa were unaffected after gas treatment. Five species showed significant reductions after the treatment: Liquidambar formosana and Machilus breviflora ($P<0.001$), Aporusa chinensis ($P<0.01$) and Castanopsis fissa and Pinus elliottii ($P<0.05$). The tap root growth of Albizzia lebbek, Bombax malabaricum, Litsea glutinosa and Tristania conferta were also suppressed, but beyond the 0.05 significant level.

For root mass analysis (Table 5.3), seven species increased in root mass, but only Tristania conferta had a significant increase ($P<0.05$). Acacia confusa and Albizzia lebbek are legumes and have root nodules (Section 2.14). The mass of their nodules collected from the treatment tanks was 94% of their control; no significant difference was observed ($P>0.05$). The mass of Bombax malabaricum storage roots after treatment (1.74 g) was 134% of the control roots (1.30 g); no significant difference was found ($P>0.05$).

For the above-ground plant parts, Machilus breviflora showed a significant difference in stem mass ($P<0.05$). Liquidambar formosana and Tristania conferta showed differences in leaf mass, at 0.01 and 0.05 significant levels, respectively.

Table 5.3 shows the Student's "t" values of the six growth variables, namely leaf number, leaf weight, plant height, stem weight, maximum root length and root weight, compared with the control groups and treatment groups. A positive "t" value

Table 5.3 Growth characteristics of the 10 species after fumigated with simulated landfill gas as percent of control. [All data are means of 10 replicates; distinct classes between LGS and HGS, according to Student's t test: *P<0.05, **P<0.01, ***P<0.001; NC: not counted].

Species	As percent of control					
	Height	Stem mass	No. of leaves	Leaf mass	Maximum root length	Root mass
Acacia confusa	98	103	108	99	101	101
Albizzia lebbek	112	115	114	128	96	94
Aporusa chinensis	101	93	110	92	78**	115
Bombax malabaricum	81*	98	87	88	68	124
Castanopsis fissa	102	100	87	95	78*	79
Liquidambar formosana	64***	87	78**	66**	56***	91
Litsea glutinosa	113	102	92	91	95	103
Machilus breviflora	96	136*	73	88	58***	131
Pinus elliottii	88	92	NC	97	81*	103
Tristania conferta	78**	91	68**	76*	85	135*
Average "t":	-0.95	-0.04	-1.09	-0.99	-4.34	0.42

indicates that the growth variable of the treatment plant was superior than that of the control, whereas a negative value was inferior. The absolute "t" values for the variables of maximum root length and root mass were the highest, indicating that the effects of landfill gas were mainly on roots. The root mass got positive average "t" values, meaning that the landfill gas stimulated root growth with respect to mass. The maximum root length had the highest negative value, showing that the tap root growth of plants was greatly suppressed. For the other variables, height got a similar value as the number of leaves, indicating that the effects of gas on these two variables were similar. The average "t" of stem mass got the lowest negative value, indicating that gas suppressed stem growth, but the effects were lower in comparison with the influence of other variables.

5.3 Summary

Simulated landfill gas was fed into study tanks to fumigate the roots of 10 species. The soil methane, CO_2 and O_2 concentrations were adjusted close to the soil landfill concentration in the HGS of GDB landfill.

After the six-weeks continuous gas treatment, most species showed suppressed apical root growth, but increased root mass; the stimulated horizontal growth of adventitious roots formed a flattened root system in the middle level of the study tanks. Chlorosis, a reduction in leaf size and stunted growth were observed in some plants.

CHAPTER 6

DISCUSSION

6.1 Tree growth on field sites

Adverse tree growth in completed landfills has been experienced in Hong Kong and other countries (Section 1.53). A high landfill gas concentration in the cover soil has been suggested as one of the major reasons for the inferior tree growth. However, this assumption lacks experimental data to support it. In order to find out the relationship between landfill gas and tree growth, a one-year field study from July 1988 to June 1989 was conducted at the Gin Drinkers' Bay (GDB) landfill site (completed for ten-years), Hong Kong (Chapter 4). A total of 200 tree seedlings, belonging to 10 species and 8 families, was transplanted to two sites there. One site had a high concentration of landfill gas in the cover soil (high-gas-site, HGS), while the other had a relatively low concentration of gas (low-gas-site, LGS). Throughout the project period, all species on the HGS showed inferior growth and higher mortality rates than on the LGS. As the soils in both sites showed no significant differences in general properties and nutrient contents (Table 3.1), the differences in tree growth are apparently not caused by the differences in the soil mineral contents. Moreover, the absolute values of TKN, P and K on the HGS were slightly higher than on the LGS. If the soil nutrient content had played a determining role in growth, plants on the HGS should have had superior growth compared to the plants on the LGS.

Among the 10 species, some species appeared much more tolerant to the landfill environment than others. A dial ranking system, which included the relative viability of plants and relative growth of surviving plants, was used to show the differences (Gilman *et al*., 1981a). The viability rates of *Acacia confusa*, *Albizzia lebbek* and *Tristania conferta* were high~~est and were on the higher rank~~ (Table 6.1). These three species, together with *Litsea glutinosa*, were studied on the same landfill by Wong *et al*. (1987)(Table 1.3). The seedlings investigated by these authors were of the normal sizes suited for transplantation, about 0.5 - 1.0 m in height. The mortality rate they reported was based on the number of trees assumed to be dead or in extremely poor conditions and needing to be replaced (Section 1.53). The mortality rates of these four species were close to those of the present study, in which younger seedlings were used.

The experimental seedlings in the present study were left at the sites to permit further observations. Therefore, the total mass of the surviving seedlings was unknown and had to be predicted from other growth variables. Different authors have used different variables to estimate the total mass and growth of trees, such as base diameter (Hytonen, 1985), height (Ettala, 1987) and leaf area (Fitter and Hay, 1987). No one variable is ideal for all circumstances. A relative comprehensive method involving four variables (height, base diameter, number of leaves, leaf size) and adapted from Gilman *et al*. (1981a) is used. This method compares the growth variables between two treatment groups and uses the average Students' "t" values to justify the overall performance of trees. The average "t" values

Table 6.1. Ranking of the 10 species of trees with respect to their overall performance in the field and laboratory studies.

[* the smaller the number, the higher the relative survival rate, see Section 4.2,

@ based on the average "t" values of the variables of height, base diameter, leaf size and number of leaves. The smaller the number, the less is the difference between LGS and HGS, see Table 4.6,

based on the average "t" values of the variables of height, stem mass, number of leaves, leaf mass, maximum root length and root mass. The smaller the number, the higher in sensitivity, see Table 5.3]

Species	Field study		Laboratory study
	Relative survivial rate	Relative growth	Sensitivity to landfill gas
<u>Acacia</u> <u>confusa</u>	4*	1@	9#
<u>Albizzia</u> <u>lebbek</u>	1	5	10
<u>Aporusa</u> <u>chinensis</u>	7	2	7
<u>Bombax</u> <u>malabaricum</u>	3	7	6
<u>Castanopsis</u> <u>fissa</u>	10	9	5
<u>Liquidambar</u> <u>formosana</u>	6	3	1
<u>Litsea</u> <u>glutinosa</u>	8	4	8
<u>Machilus</u> <u>breviflora</u>	8	9	2
<u>Pinus</u> <u>elliottii</u>	4	6	4
<u>Tristania</u> <u>conferta</u>	1	8	3

of the four growth variables are compared and ranked in Table 6.1. *Acacia confusa* was the least sensitive tree to landfill conditions and *Tristania conferta* was one of the most sensitive.

Under most circumstances, relative viability is of more concern for landscaping purpose than relative growth. Based on the viability rate and the general appearance of the trees, the performance of the 10 species may be classified subjectively into three classes. *Acacia confusa*, *Albizzia lebbek* and *Tristania conferta* are suited for growth on former landfill sites. *Bombax malabaricum* and *Pinus elliottii* can be considered for use, but need extensive care. *Aporusa chinensis*, *Castanopsis fissa*, *Liquidambar formosana*, *Litsea glutinosa* and *Machilus malabaricum* are unsuitable.

6.2 Influence of landfill gas on tree growth

To investigate the physiological effects of landfill gas on trees, a laboratory study was conducted (Chapter 5). The results revealed that the presence of high landfill gas in soil did not have acute lethal effects on trees, but induced a flattened shallow root system.

Although methane concentrations in the GDB landfill cover soil (Section 4.1) and in the laboratory simulation study (Section 5.1) showed a strong negative correlation with adverse tree growth, as reported in different countries and by different authors (Ettala, 1988b; Flower, *et al*., 1981; Wong *et al*., 1987; Wong; 1988), methane itself is inert to plants (Section 1.511), and has no direct influence on tree growth. The flammable property of methane (Section 1.511) makes it of high civil engineering concern and must be monitored closely in every landfill site. Moreover, as its concentration in landfill soil is usually in correlation with the concentrations of CO_2 and O_2 (Sections 1.51 and 4.1), its concentration in soil can be regarded as an indirect indicator for the presence of high CO_2 and low O_2.

In the study tank, profiles of CO_2 and O_2 and three zones (A, B, C) of root growth were established (Fig. 6.1). As the simulated landfill gas was fed directly into the tank bottom, the soil atmosphere there (Zone C) was virtually pure gas; the CO_2 concentrations were around 30% - 50%. In the middle level of the tank (Zone B), where the gas was diluted by ambient air, the CO_2 concentrations were about 5% - 30%. Zone A indicated the top soil layer where the soil air was similar to ambient air.

The inhibitory and stimulatory effects of CO_2 (Section 1.512) were demonstrated in the gas treatment study. In the tank bottom (Zone C), tap root growth of most plants was suppressed by a high concentration of CO_2, indicated by the significant reduction in maximum root length after treatment (Table 5.3). The soil in the middle level of the tank was of the Zone B condition. In this zone, the medium concentration of CO_2 stimulated the longitudinal growth of adventitious roots. As the roots could not penetrate into Zone C, they formed a horizontal roots system in Zone B. Penetration of light and occasional drying out limited the root growth in Zone A. Under laboratory conditions, the top soil was covered by a plastic sheet to prevent excessive diffusion of ambient air. The top soil never dried out.

In a natural environment, a CO_2 profile develops in semi-

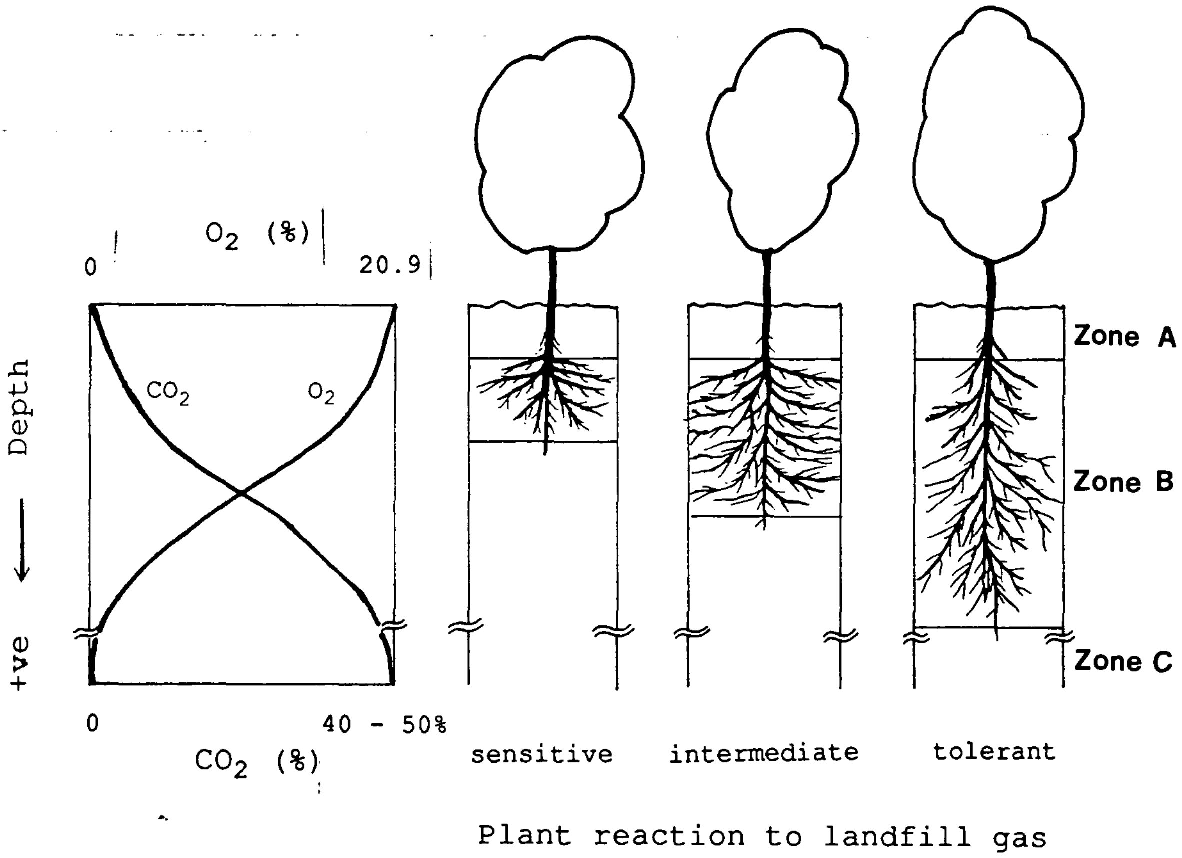


Fig. 6.1 Carbon dioxide and O_2 contents of landfill soil atmosphere in relation to depth, and zonation of root growth.

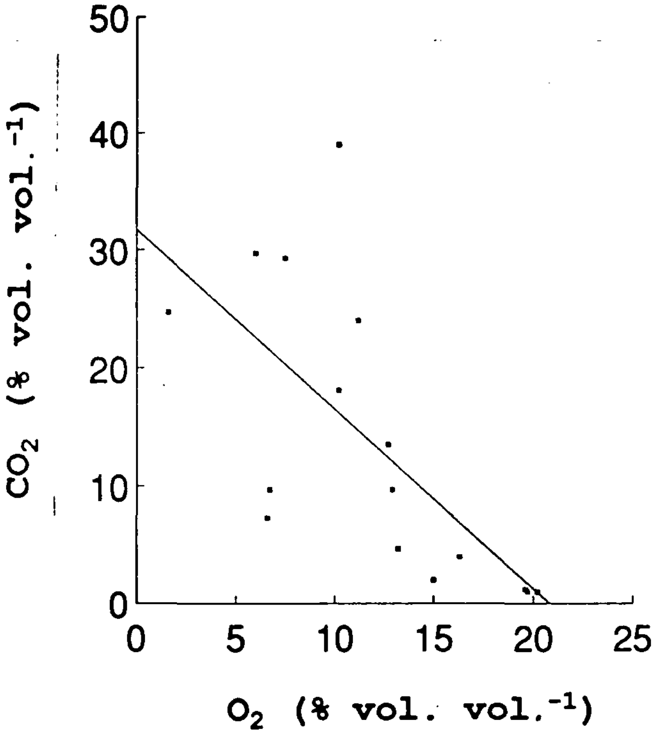
Penetration of light and occasional drying make Zone A unsuitable for root growth. In Zone B, root growth is stimulated by low conentrations of CO_2. Zone C is restricted for root growth by high conentrations of CO_2 (>20%) in soil. For plants with roots sensitive to CO_2, they have a shallow system in Zone B. Trees with moderate sensitivity to CO_2 have a medium thickness of Zone B for root growth. Trees tolerant to high CO_2 concentrations have a deep root system.

drained soil but the maximum CO_2 concentration usually does not exceed 10% (Carr, 1961). In landfill soil, the gradient of CO_2 profile is much steeper than in normal soil and may reach a high concentration of 40% (Guter and Nuerenberg, 1987). The maximum depth of the root system of a tree, that can be developed in a landfill site, depends on the sensitivity of the tree to CO_2. For trees with a low CO_2 threshold, roots are limited to a thin Zone B. Trees with moderate sensitivity to CO_2 have a moderate Zone B thickness; the stimulated growth of adventitious root forms a wide spreading root system in this Zone. Trees with a high threshold to CO_2 have a thick Zone B for growth.

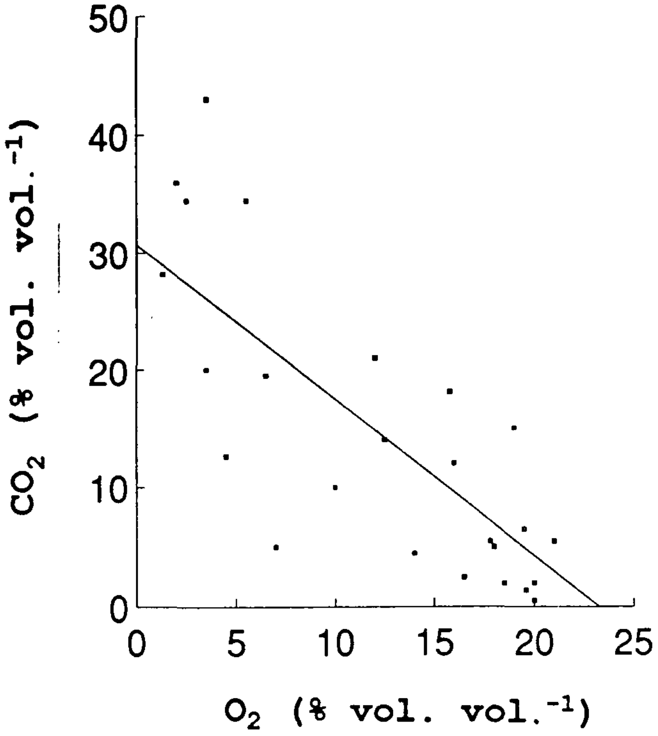
O_2 depletion is suspected to be a limiting factor for tree growth on former landfills (Flower <u>et</u> <u>al</u>., 1981; Leone <u>et</u> <u>al</u>., 1977b). Which factor is the more critical, high CO_2 or low O_2? The absolute concentrations of CO_2 and O_2 in soil determine which gas plays the more important role in influencing root growth. To compare the concentrations of these two gases in landfill soil, regression analyses were carried out (Fig 6.2.A and B). The concentrations of these two gases in the GDB landfill showed a strong correlation with each other (N = 16, r = -0.68). Data from different countries and different soil depths showed a similar correlation (N = 31, r = -0.78). From these two regression lines, the O_2 concentrations in landfill soil can be predicted by using the CO_2 concentrations. When CO_2 concentrations are about 5%, 10%, 15% and 20%, the O_2 concentration are about 16%, 14%, 12% and 10%, respectively. Medium concentrations (5% - 15%) of CO_2 stimulate root growth in plants (Section 1.512); the corresponding O_2 concentrations

Fig. 6.2.A. Correlation analysis between CO_2 and O_2 concentrations in GDB landfill cover soil (see Table 4.1 & Section 6.2).

Fig. 6.2.B. Correlation analysis between CO_2 and O_2 concentrations in landfill soil, data from different countries and authors: Gilman *et al.*, 1982 and 1982, Sin, 1981, Leone *et al.*, 1977, Leone and Flower, 1984 and Wong *et al.*, 1987 (see Section 6.2).



50
40
30
20
10
0
0
5
10
15
20
25
CO_2 (% vol. vol.$^{-1}$)
O_2 (% vol. vol.$^{-1}$)



50
40
30
20
10
0
0
5
10
15
20
25
CO_2 (% vol. vol.$^{-1}$)
O_2 (% vol. vol.$^{-1}$)

are about 16% - 12%. It is unlikely that the root growth of plants is affected at these concentrations of O_2 (Section 1.513). When the CO_2 concentrations in soil are raised above 15%, root growth is inhibited in most plants (Section 1.512). Under these concentrations of CO_2, the O_2 concentrations in soil are about 10% - 12%, and will cause fewer effects on normal root growth (Section 1.513). Therefore, for plants with normal sensitivities to CO_2 and O_2, it is the concentration of CO_2 in landfill soil which plays the more important role and determines the pattern of root growth.

The gaseous composition in landfill soil is never stable, it has a seasonal pattern (Section 4.1) and also fluctuates daily under the influence of soil moisture, temperature, atmospheric pressure and other climatic factors (Guter and Nuerenberg, 1987). Temporary exposure to a high CO_2 can be registered by roots, and exerts effects on plants (Geisler, 1963). Under temporary low O_2 stress, most plants can use any of the methods illustrated in Section 1.513 to transport O_2 from other parts, or undergo anaerobic respiration to pass the stress period. Therefore, short-term exposure to a high CO_2 concentration causes long-term effects, and short-term exposure to a low O_2 concentration has less influence on plants. This makes the influence of CO_2 more significant than O_2 on plants.

The relative influences of CO_2 and O_2 were demonstrated in the laboratory study. Three trees showed that their roots could tolerate extremely low concentrations of O_2 and at the same time their root growth was affected by CO_2. The average O_2 content measured in the fumigation tank of Bombax malabaricum was extremely low (0.5%, Table 5.1). Under this low O_2

concentration, roots of B. malabaricum survived and, probably stimulated by CO_2, increased in root mass. Castanopsis fissa also demonstrated that its roots could tolerate a 0.9% O_2 concentration in rhizosphere. The roots of Acacia confusa grown on soil with pure landfill gas indicated that it could tolerate an extremely low O_2 content. Moreover, the white flaky substances found on the surfaces of A. confusa roots after gas treatment indicated that its roots had been exposed to a high CO_2 atmosphere. These white flaky substances are carbonate and bicarbonate salts, which form in the presence of high CO_2 (Hook et al., 1971).

The laboratory results indicated that CO_2 mainly affects root growth, but other effects on the shoot should not be overlooked. After the gas treatment, the green pigment in Liquidambar formosana leaves was reduced; chlorosis was caused by root exposure to high CO_2 (Hook et al., 1971).

In the field study, no general changes in stomatal resistance were observed with respect to the soil gas concentration: some species increased and others decreased (Table 4.5). Ettala (1988) reported that the stomatal resistance of Salix aquatica in landfill was dependent on the soil moisture and independent of soil temperature and gas content. However, Arthur at el. (1985) reported that the stomatal resistance of sugar maples, fumigated with simulated landfill gas, was significantly increased. The exact influence of soil gas on stomatal movement needs further investigation.

6.3 Common characteristics of trees suited for growth on subtropical landfills

In completed landfill sites root growth may be influenced adversely by two key factors: a gas factor in deep soil (Section 6.2) and a water factor in top soil. The influence of water stress on drought sensitive trees with shallow root systems was revealed by some species in the study: Aporusa chinensis, Castanopsis fissa, Liquidambar formosana, Machilus breviflora. They were sensitive to CO_2 and had a shallow root system, indicated by the significant reduction in their maximum root length and root mass after the gas treatment (Table 5.3). Their viable seedlings on the HGS were xeromorphic and reduced in size (Figs 4.5); these are typical morphological changes in response to water stress (Fitter and Hay, 1987). Moreover, the coincidence of their high mortality rates with the drought period from September to December 1988 (Fig. 4.2) indicated that they died of desiccation. The soils in HGS and LGS had similar water contents (Table 3.1). The seedlings of a species grown on HGS expressed symptoms of water stress, but the seedlings of the same species on LGS showed normal growth, indicating that the former seedlings failed to develop an effective water acquisition system. Plants in drier habitats tend to develop deep and/or extensive root systems (Fitter and Hay, 1987). However, deep or extensive root systems are restricted by landfill gas. Due to the above reasons, drought resistance species should be more suitable than drought sensitive species for growth on landfill sites.

High temperature is another kind of stress in landfill which limits tree growth. Areas with gas problems are usually relatively bare (Section 3.4) and the top soil temperature in such areas may rise to above 45°C in summer (Section 3.3). Such a high temperature is not only due to severe irradiance, but also due to self-heating (Section 1.52), and has been experienced on HGS (Table 3.1). Trees with a deep root system are less susceptible to top soil thermal stress. However, as discussed in the preceding section, trees grown on landfill cover generally are shallow rooted and become susceptible to thermal stress.

Among the 10 species, two legumes, _Acacia_ _confusa_ and _Albizzia lebbek_, were two of the three most suited for growth on landfill sites (Section 6.1). The superior growth of these legumes was not due to nitrogen fixation ability. The nitrogen contents in HGS soils (Table 3.1) were within the normal ranges of top soil in sub-tropical forest (Armstrong, 1975) and inferior tree growth on HGS should not be due to nitrogen deficiency. High resistance to landfill gas might be one of the reasons. Such tolerance was indicated by the growth of _Acacia_ _confusa_ roots on pure landfill gas (Section 5.2). Maximum root length was not affected in _the_ case of _Albizzia_ _lebbek_ (Table 5.3) and no significant changes in nodule mass in either species was detected (Section 5.2) after gas treatment. Nodules need O_2, CO_2, N_2 and H_2 for optimum gaseous exchange (Sprent, 1984), and these gases are readily available in landfill soil (Section 1.514). Carbon dioxide at a low concentration is beneficial for nodule growth. Nutman (1980) demonstrated that the presence of 0.1% CO_2 increased the yield of _Rhizobium_ cells. However, information about the responses of nodules to long-term exposure to high CO_2 is not available.

Generally, nodules are tolerant to a low O_2 environment. They can obtain O_2 from other tissue (Sprent, 1984) and have leghaemoglobin to bind O_2 reversibly (Bergensen, 1980). Moreover, legumes included in the family Mimosaceae are often well adapted to arid areas (Sprent, 1984). Their high resistance to water stress may be another adaptive feature for growth on landfill sites. Other legumes in Hong Kong belonging to the same family that may be suitable for growth on completed landfills are: Abarema lucida (suitable for wasteland), Acacia decurren, A. pennata (fast-growing evergreen), Adenanthera pavonina (rapid growing), Albizzia julibrissin (deciduous, with gracefully spreading branches), Leucaena leucocephala (an urban plant) and Samanea saman (deciduous)(Thrower, 1988).

Tristania conferta was one of the most sensitive species to landfill gas (Table 5.3) and also was one of the best suited species for growth on landfill sites (Section 6.1). Fig. 6.1 helps to explain this phenomenon. The adventitious root growth of T. conferta was stimulated by CO_2 (Table 5.3), but vertical root growth was suppressed slightly. Therefore, it had a certain depth of Zone B for root growth and had a wide spreading root system to search for water and soil with a low landfill gas concentration. However, the sensitivities of common trees with landscaping values to CO_2 are not compared, and we cannot depend on this criterion to select tree species for growth on landfill sites. An alternative criterion is to select according to the growth rates, which are readily available (Section 1.3, Table 2.1). In situ studies proved that fast-growers (Acacia confusa, Albizzia lebbek and Tristania conferta, Section 4.3) were more suitable for growth on landfill sites. In contrast, the slow-growers Aporusa chinensis, and Litsea glutinosa, failed to develop a wide spreading root system in landfill, and had inferior growth on study sites.

Besides a wide spreading root system, fast-growers have another superior feature. During the in situ and laboratory studies, Acacia confusa, Albizzia lebbek and Tristania conferta tended to shed their leaves continuously, especially T. conferta. It is generally true that old leaves have a much higher salt or heavy metal content than young leaves. Amelioration, by passively accumulating the toxin in old leaves, followed by abscission (Fitter and Hay, 1987), might help these seedlings adapt to the landfill environment.

6.4 Concluding remarks

Besides the above mentioned gaseous and non-gaseous factors that can influence the growth of trees under landfill conditions, there are many other adverse factors in the landfill environment. The presence of these factors was indicated by the following: Acacia confusa and Albizzia lebbek showed no adverse effects in the laboratory studies, but physiological disorders were observed on HGS; Liquidambar formosana leaves lost their green pigment and became pink green or white after gas treatment, but young and old leaves of L. formosana on HGS turned to brownish red. These factors may be any toxins on landfill soil, or other physical factors (Section 1.52) or the combination of many factors.

The influence of landfill gas on the root growth of trees and some of the causes of the mortality of trees on landfill sites were explained. The common characteristics of trees suited for growth on subtropical landfills were discussed. However, the success of revegetating completed landfills is highly dependent on soil irrigation, soil texture, thickness of cover, nutrient contents in the soil and the daily care of the plants.

SUMMARY

a) A study, combining both field and laboratory controlled experiments in Hong Kong, was carried out on the influence of landfill gas on 10 tree species, belonging to eight families.

b) Gin Drinkers' Bay (GDB) landfill showed seasonal variation in soil landfill gas concentration. The methane concentration was correlated positively with air temperature, while the O_2 concentration was correlated negatively with air temperature. Moreover, the O_2 level was inversely proportional to the concentrations of methane and CO_2.

c) Two sites were selected in the GDB landfill for study: one with a high mean landfill gas concentration and the other with a very low landfill gas concentration. The chemical properties of soil at the two sites showed no significant differences. Species diversity, the percentage cover of vascular plants, the mass of above-ground plant parts, and ground litter at the study sites were all inversely proportional to the concentration of landfill gas.

d) Tree seedlings were transplanted to the GDB sites to evaluate their growth under real landfill conditions. High mortality rates were related strongly to the presence of landfill gas. Viable seedlings grown on high-gas-sites were reduced in height, base diameter, the number of leaves and the size of leaves. Premature senescence, chlorosis and blight were also observed.

e) A controlled laboratory experiment was performed to study the influence of landfill gas on the trees. Roots of seedlings were fumigated with simulated landfill gas. The gas feed in rate was controlled, and made the methane, CO_2 and O_2 concentrations in the soil very close to the concentrations on the high-gas-site.

f) The laboratory test showed that the effects of landfill gas varied greatly among species. Roots of Acacia confusa grew downwards, regardless of the presence of landfill gas. Roots of the other nine species grew horizontally or upwards in the soil. Except for Acacia confusa, the maximum root lengths were reduced. Seven species increased their root mass after the treatment. Three species (Bombax malabaricum, Liquidambar formosana, Tristania conferta) showed a more marked reduction in height and a smaller number of leaves than others.

g) Under the influence of landfill gas, horizontal growth of adventitious roots may be stimulated and tap root growth hindered. The shallow root system helps the plant to search for places with a low landfill gas concentration and water resources, and avoids the uptake of toxic materials embedded under the landfill cap. However, if the root cannot tolerate temporary drought and temperature stress, the shallow root system is lethal to the plant as the top soil occasionally dries out, and the temperature may exceed 40°C in the summer.

h) Fast-growers are more suited for growth on landfill sites than slow-growers. Continuous shedding of leaves in fast-growers helps them to excrete accumulated toxin. Two legumes, Acacia confusa and Albizzia lebbek, showed superior performance on the landfill site and proved tolerant to a high landfill gas concentration. The mass of root nodules in these two species was not changed after landfill gas treatment.

i) The results of the project showed that landfill gas was an influence on tree growth, but it is not the only factor causing poor growth of trees under landfill conditions. Some species which appeared sensitive to landfill gas under laboratory conditions, had superior growth on a high landfill gas environment, and vice versa. Symptoms developed on trees after the influence of landfill gas, differed from the symptoms developed on the field sites. The above observation indicates that there are other factors co-existent with the landfill gas, which are present on the landfill environment and which affect plant growth.

j) The results of the in situ and laboratory growth study showed that Acacia confusa, Albizzia lebbek, and Tristania conferta are suited for growth on former landfill sites. Bombax malabaricum, Pinus elliottii can be considered for use, but need extensive care. Aporusa chinensis, Castanopsis fissa, Liquidambar formosana, Litsea glutinosa and Machilus malabaricum are not suited for use.

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APPENDIX

THE DESIGN OF GAS VOLUME FLOW METER

The success in construction of 10 home-made flow meters made the precise control of simulated landfill gas fed into study tanks became possible (Section 2.21 to 2.23). The design of the apparatus is shown in Fig. A. and is modified from Mosey's device (Mata-Alvarez et al., 1986) and Triton Brand gas volume meter Model 181 (Triton, 1987). Each meter consisted of two chambers, the inner chamber and the outer chamber. These two chambers were connected at the base and by a U-tube. The function of the U-tube was to equalize the pressure in the chambers. Before start, each meter was filled with 500 ml of water. Gas sample to be measured was directed to the inner chamber via the inlet, and it developed a positive pressure there. The pressure displaced the water until the lowest level was reached. At this level, gas passed from the inner chamber to the outer chamber via the communicating U-tube; the pressure in the chambers became equal and the water in the inner chamber raised back to the highest level. When the water level in the inner chamber fell, the water level in the outer level rase. Every time the water level in the outer chamber reached the sensing electrode, an electrical signal was sent to a counter. The counter was modified from a dry battery operated calculator; each time it received a signal, a constant value was added and the sum was displayed. After each cycle, gas was forced out from the outer chamber via the outlet. The exact volume of gas passed through on each cycle varied and depended on the height of the U-tube; therefore, all the meters were calibrated individually by water displacement method. The exact volume of gas displaced on each cycle had been input to the counter, so that the figures displayed by the counter indicated directly the volume of gas passed through it.

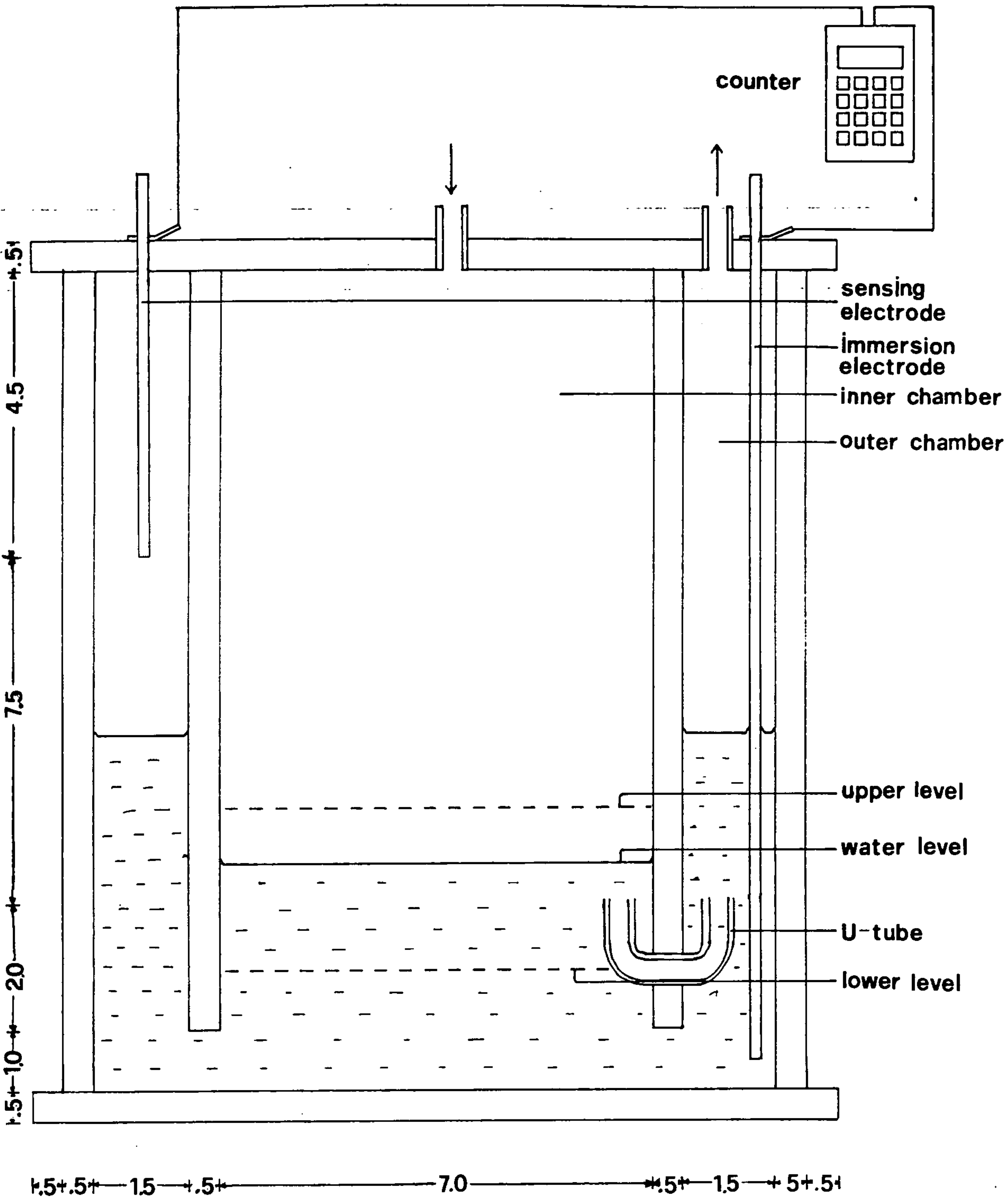

Fig. A   Detail of flow meter. (diamensions in cm)