Techniques for microclimatic modification to assist the establishment of vegetation in dry areas : an assessment of mulching and other techniques to assist plant establishment in dry areas on landscape projects

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Publication Date:
1988

DOI:
https://doi.org/10.26190/unsworks/8324

TECHNIQUES FOR MICROCLIMATIC MODIFICATION TO ASSIST THE ESTABLISHMENT OF VEGETATION IN DRY AREAS

(An Assessment of Mulching and Other Techniques to Assist Plant Establishment in Dry Areas on Landscape Projects.)

by

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30th October, 1988

ABSTRACT

The specification of plants and of planting techniques form a major part of the activities of a landscape architect. They are critical steps towards ensuring plant survival and growth, and as such can significantly influence the overall success of a design. This thesis addressed the problems associated with specifying techniques for assisting plant establishment in dry areas on landscape projects.

Irrigation, windbreaks, weed control, site preparation and planting techniques were assessed for their effectiveness in increasing the levels of available soil water. The importance of adequate site inspection and analysis was clearly identified. This enabled the design of specific solutions to the problems of planting in dry areas, using the palette of techniques covered. Practical applications of the techniques covered were shown by means of typical details.

Particular attention was paid to the practice of mulching, both in research and supplementary experiments. From the work undertaken, the thermal diffusivity of a mulch appears to be a reliable indicator of its efficiency in both evaporation reduction and soil temperature modification. Loose organic mulches were found to have thermal diffusivities that were lower and less variable than inorganic mulches, and should thereby prove more effective in ameliorating the causes of dry areas than inorganic mulches.

ACKNOWLEDGEMENTS

Thanks are due to the following people for their assistance, encouragement and patience: my parents, Col. Ron and Elza Garland; my wife Adele; Dr Max and Marianne Bern; Dr Syd and Joan Baggs; Dr Julianne Venning; Mr Craig Burton; Mr Stuart Pittendrigh; Ms Carolyn Tallents; Prof. Richard Clough; Assoc. Prof. Finn Thorvaldson; and the staff of the Sydney Bureau of Meteorology.

CERTIFICATE OF ORIGINALITY

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institute of higher learning, except where due acknowledgement is made in the text.

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CHAPTER I

THE CAUSES OF DRY AREAS AND THEIR AMELIORATION

INTRODUCTION

The specification of plants and of planting techniques forms a major part of the activities of a landscape architect. They are critical steps towards ensuring plant survival and growth, and as such can significantly influence the overall success of a design. Designs displaying poor plant selection and/or inadequate provision for their establishment, typically incur considerable post-planting expenses. These include costs of plant replacement and increased maintenance. The integrity of the design is also placed at risk when failed plants are replaced with other species without consulting the designer. These problems are common, as was evidenced by the need for a 'Specified•Planted•Died Seminar' as recently held in New South Wales.[1]

One reaction to this problem is to provide designs specifying only known versatile, hardy and reliable

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[1]Specified•Planted•Died Seminar, June 24, 25 1988, Robertson, Southern Tablelands, N.S.W. (no proceedings available)
Landscape Co-ordination Working Party (TAFE + AILA + LCA)

species. This is even sound practice in areas of a design which provide limited resources for plant survival and growth, such as shallow, sandy soils in exposed areas. However, it can lead to the over-use of a fairly limited range of plant species, which in turn sees a drop in the diversity of plants grown by nurseries.

A more balanced approach to the problem requires a clearer understanding of the components involved. Specifically, the specification of plants should entail the selection of species capable of growth in the given conditions. Any techniques applied for plant protection and support, such as soil preparation, mulching and irrigation, should provide suitable conditions to enable plant survival until establishment. That is, techniques for assisting plant establishment should not be expected to enable on-going survival and growth of species that are poorly suited to a site. Designs based on this expectation will inevitably result in plant failure and/or increased maintenance costs.

The process of selection of a palette of suitable plant species with which to work can prove a detailed task, and has to be reviewed for each new set of conditions. This is both an important and complex issue, and is beyond the scope of this work. However, in the writer's opinion, this is one area of Landscape Architecture where computers can prove extremely useful with their ability to store and selectively retrieve images and text.[2]

This thesis specifically addresses the problems associated with specifying techniques for assisting plant establishment. This is not always an easy task, and is further complicated by an increasing demand in commercial and private sectors for highly advanced, low-maintenance plantings. Due to increasing labour costs, the level and quality of post-planting maintenance is decreasing proportionately. Consequently, more onus is being placed on the designer to specify techniques, for implementation during site preparation and planting, which will help ensure the growth and establishment of the selected plant species.

While many of the techniques covered are of general application, the specific context of this thesis is that of landscape projects in Australian urban and suburban areas. The qualification of 'dry areas' in the thesis topic is based on the definition of dry areas as any areas where lack of available soil water presents a major threat to the survival and growth of the selected plant species. This definition is purely functional and depends to a large extent on the water requirements of the selected plant species, and even on those of individual specimens. Mature, container-grown trees, for example,

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[2]It should be noted that some packages, such as Plant Guide by Arbordata, are already available and in use, often to good effect.

frequently have a high-volume water requirement which initially has to be satisfied through a relatively confined root system. Therefore, corresponding measures have to be taken to meet this demand until this root system can develop and penetrate the surrounding soil.

The thesis is concentrated on urban and suburban projects as the advanced, semi-mature and mature plants typically used represent a considerable investment on a dollars/plant basis, especially in comparison to broad-scale revegetation projects. Hence the survival of individual plants is a more significant concern than in the latter case, where survival rates as low as 75% may be acceptable (Venning, 1988, p. 1).

The focus on dry areas (as defined above) is justified since water is one of the fundamental requirements for plant survival and growth, especially during the period of plant establishment.[3] To this end, the techniques investigated are those that are potentially capable of increasing the amount of water available to the plant. Particular attention has been paid to the practice of mulching, both in research and supplementary experiments. Although mulching is in wide use and commonly accepted as beneficial, there are very little comparative data available to assist in the selection of the most appropriate mulch

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[3]In the context of this work, plants are considered established when they require no further artificial assistance to grow in the given environment.

materials. Although statements that imply a comparative basis can be found in the literature on mulches, they are invariably poorly qualified, unfounded, or untrue. For example, Hanks and Ashcroft (1980, p. 88) state that "one of the most efficient mulches...is pea gravel", yet they apparently base this claim on a non-comparative study by W.D. Kemper showing the effect of increasing storage of precipitation by increasing the depth of pea-gravel mulch from zero to one, two and three cm. Similarly, Blake's (1967, p. 17) claim that "all mulches reduce the variations in the temperature within the soil." is not only unfounded, but is in stark contradiction to the existing literature.[4]

In summary, this thesis was undertaken to provide essential information for the process of selecting techniques to assist plant establishment. It is anticipated that this work will enable specification of techniques based on a clearer understanding of what their effect will be on the plant and its environment, and consequently help reduce the level of plant failure on landscape projects.

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[4]Army and Hudspeth (1960) and Clarkson (1960) had previously found that variations in soil temperature are increased by application of a black plastic mulch.

THE FIELD WATER BALANCE

Addressing the problem of how to increase the amount of water available for use by plants necessitates consideration of the hydrological cycle at the level of the plant's environment. Hillel (1972, p. 80) refers to this as "the field water balance". Figure 1 displays an adaptation of Hillel's field water balance schematic to suit the context of this thesis.

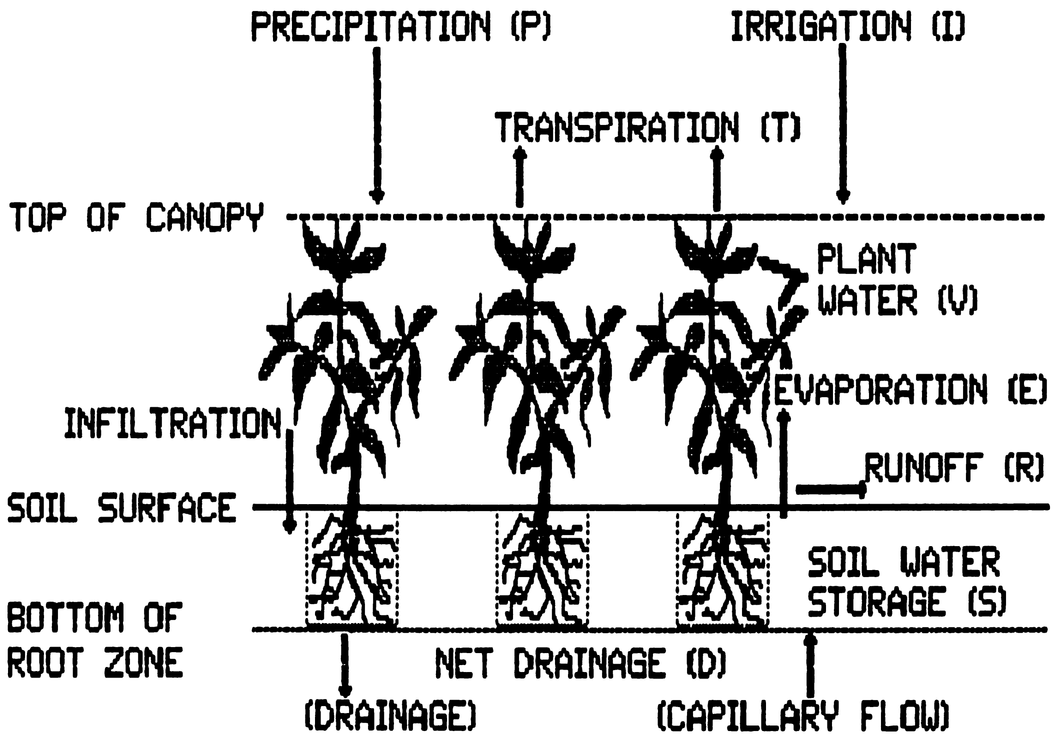

FIGURE 1: The field water balance (schematic) viewed within the context of recent, container-grown plantings. (Adapted from Hillel (1972, p. 80).)

The descriptions used above are essentially those used by Hillel with the exception of the Net Drainage term (**D**) and Capillary Flow, which Hillel described as "Deep Percolation (D)" and "Capillary Rise" respectively. This distinction has been made to include the lateral aspects of soil water flow, which are significant in the given context of plants with confined root zones.

Three distinct sets of processes can be identified from Figure 1. These are: water gains; water losses; and changes in water storage. Changes in the amount of water stored in plants (**δV**) and soil (**δS**) must be equal to the water gained through precipitation (**P**) and irrigation (**I**) less the water lost through runoff (**R**), drainage (**D**) and evapotranspiration (**E + T**). That is,

[Changes in Storage] = [Gains] - [Losses], or

$$(\delta S + \delta V) = (P + I) - (R + D + E + T) \quad [5]$$

It is apparent from this equation that the amount of water available for plant use (a component of the soil water storage (**S**) term) at any time is dependent on: the level of water gains; the level of water losses; and the form of water storage. Depending on the site, one or more of these parameters can often be identified as the predominant cause of a particular dry area. Examples may include:

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[5] Adapted from Hillel (*loc. cit.*). It should be noted that infiltration is included implicitly in this equation as the difference between water gained and water lost through runoff and surface water evaporation.

low-rainfall areas; fast-draining sandy soils; high-runoff (poor infiltration) soil surface; and weed-infested sites.

The main causes of dry areas outlined by Venning (1988, p. 30) are consistent with the above examples: "climatic factors, soil type and weed competition are the most important factors determining the success of a revegetation project because they influence available soil moisture". Although stated in the context of revegetation projects, Venning's comments are equally valid in the context of this work. Climatic factors have direct bearing on water gained through rainfall and water lost through evapotranspiration, which is influenced by insolation and wind. Soil type, while being significant, is far from being the only important aspect of the site soil. Any or all of the following can prove of equal significance: topography; soil surface condition (degree of compaction and infiltration rate); surface storage capacity; soil texture, structure, depth and water holding capacity. All of these soil-related factors may influence the amount of water lost by runoff, drainage and evaporation, as well as the maximum water storage potential of the soil.

Weed competition results in the depletion of available soil moisture through added transpiration and increased plant water storage in the weed tissue. These losses can be considerable and weed control alone can significantly improve the establishment of plants in dry areas (Venning, 1988, pp. 30-37).

Each of the techniques covered in this chapter can be specified on landscape projects in order to ameliorate one or more of the three factors outlined above. That is, climatic factors, soil-related factors and weed competition. The relationship between these factors and the techniques covered is shown in Figure 2 below.

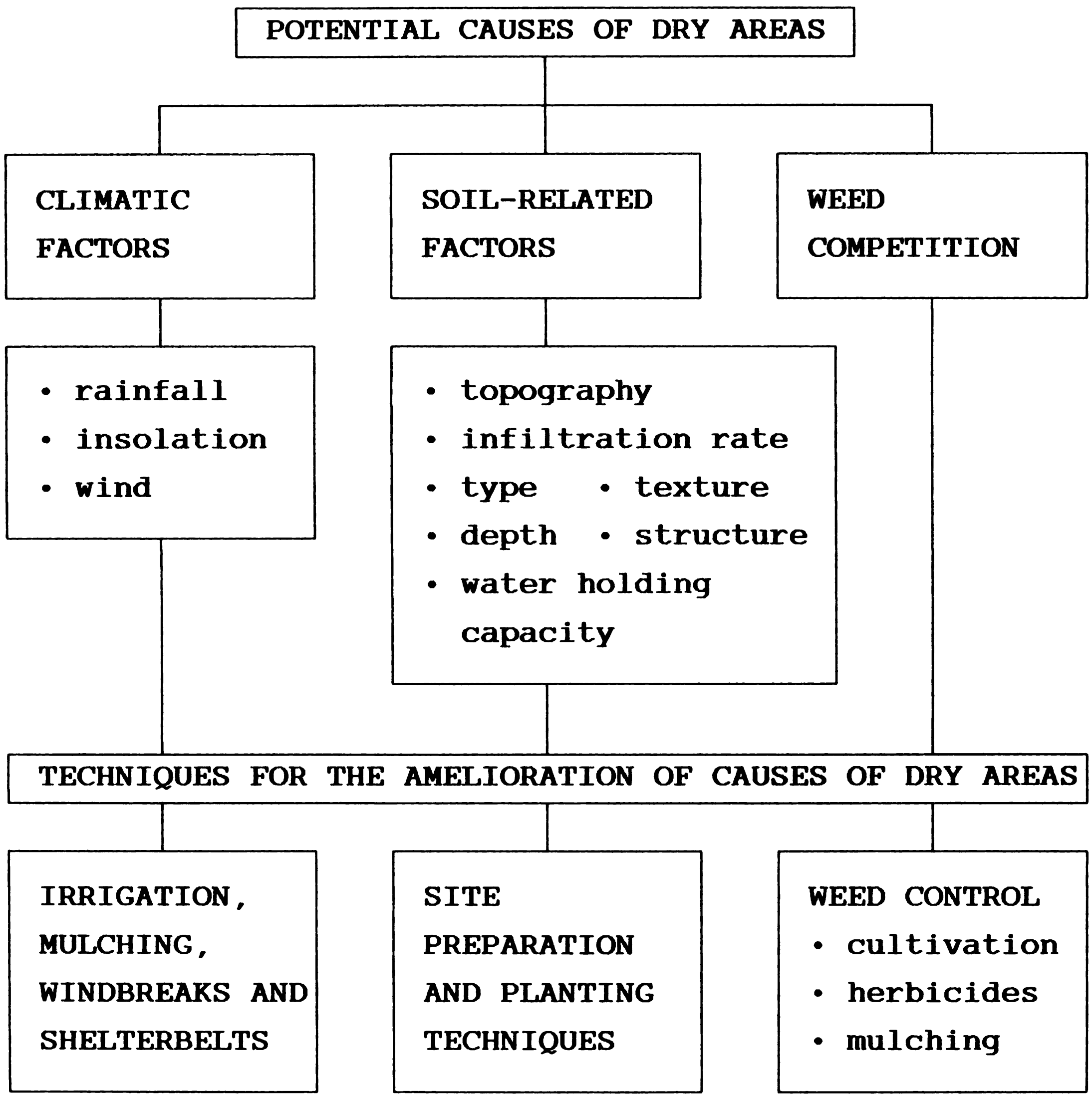

FIGURE 2: The relationship between the causes of dry areas and techniques for their amelioration.

From the techniques shown in Figure 2, irrigation, windbreaks and shelterbelts, and weed control are each considered separately. Site preparation and planting techniques, with the exception of mulching, are considered collectively in accordance with the practice of specifying them together on planting details. The practice of mulching is covered separately as, firstly, it is capable of ameliorating all of the three factors covered and secondly, it is the subject of the subsequent experimental work detailed in Chapter II.

IRRIGATION

Irrigation is the process of transporting and distributing water to plants. It can be achieved through an extremely diverse range of practices ranging from hand-cartage to fully automatic computerised systems. However the principles remain the same:

> irrigation is an agricultural practice designed to supplement a deficiency of climate: The imbalance between the water supplied by precipitation and the evaporative demands of the atmosphere. (Fuchs, 1973, p. 3)

It is important to note that the 'deficiency of climate' should be qualified by 'for the plant species selected', due to the diverse range of water requirements for differing plant species.

Within the context of this work, irrigation is considered purely as an aid to the establishment of vegetation in dry areas. This entails different requirements from the system of irrigation than would exist for agriculture in general. In the growing of commercial crops and pastures, the primary aim of an irrigation system is to achieve the maximum increase in yield as efficiently as possible (in terms of costs and resources). However, irrigation as a technique for assisting the establishment of vegetation is less concerned with the development of above-ground biomass. Its utilization is aimed at: assisting plant development during the first year of growth after planting, when plants are most susceptible to water stress; and fostering extensive root system development to assist plant survival during subsequent periods of water stress.

There are several factors that alone, or in combination, determine the type of irrigation best suited to a project. They also determine whether irrigation can or should be used to assist the establishment of vegetation in dry areas. These factors are: the scale of the project; the project budget; and the availability and quality of water.

The scale of the project and the project budget both directly influence the irrigation system design. For example, on medium to large scale projects,[6] the cost of in-ground sprinklers or trickle irrigation systems becomes

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[6]Such as the Port Botany Open Space project (Mackenzie *et al.*, 1986, pp. 94-96).

prohibitive. Irrigation requirements for large projects are usually analysed by areas, with perhaps some areas having systems installed, others having periodic sprinkler irrigation and the balance may not be irrigated at all. In any event, on large projects, as well as low-budget projects, irrigation costs often represent a substantial proportion of the total project costs. It is for this reason that Venning (1988, p. 98) states that "everything possible should be done to avoid watering after planting". In addition to the costs associated with irrigation installation and maintenance, cost of operation can also prove significant. This is especially true on sites where water suitable for irrigation usage may be located so remotely from the site that costs of conveyancing would be prohibitive. Also, available ground water may be too saline to use irrespective of the irrigation system employed.

Types of irrigation may be classified into four main categories according to their means of application of water to the plant. These are surface flow, overhead, trickle and underground irrigation. As surface (or gravity) flow irrigation is of little application in the context of this work, only overhead, trickle and underground irrigation are covered.

Overhead (Sprinkler) Irrigation

Overhead or sprinkler irrigation involves the conveying of water under pressure to release nozzles which broadcast and direct the water over the plants to be irrigated. Modern sprinkler systems have a good level of uniformity of water distribution and pattern stability. Typically, sprinklers have a Christiansen uniformity coefficient of 84% or better (Rawitz, 1973). Little or no land is required for conveyance, distribution and control of water and the amount and rate of water application is easily controlled. Overhead irrigation is well suited to soils with high infiltration rates (e.g., loamy sands), especially on uneven topography. It is also well suited for areas of grasses, ground covers or low shrubs, where other means of irrigation would prove inadequate.

However, sprinkler irrigation also exhibits several disadvantages which can prove significant within the constraints of a given project. As they fragment and cast the water through the air, sprinkler systems are very susceptible to wind drift. Wind can distort wetting patterns and increase evaporational losses. Also initial capital outlay for a sprinkler system, especially a large-scale, fully-automatic one, may be very high. Sprinkler systems typically require at least 210kPa water pressure and operating costs may be high due to pump usage and labour required to move sprinklers around. Sprinklers invariably increase local humidity around the plants, thus increasing the risk of pest and disease attack. Portable sprinkler systems cannot be fully automated and are therefore prone to human error, including neglect and under- or over-watering.

In terms of assisting plant establishment, sprinkler irrigation tends to encourage shallow rooting, which can be very detrimental in the long term (Depuit *et al.*, 1982). Sprinklers are not suitable for use with saline water as evaporation on foliage may cause leaf burn. Evaporation also leads to the accumulation of salts on the soil surface which require regular leaching.

Sprinkler systems may be classified either on the degree of portability of the conveyance system (Rawitz, 1973 and Stern, 1979), or on the radius covered by individual nozzles (Garland, 1983). The latter means of classification is adopted in this work, as the former is considered more applicable to agriculture in general than to the task on hand. Specifically, the degree of portability of the system sheds no further light on the varying effects of sprinkler systems on the soil surface and their respective wetting zones. Also, as irrigation is being considered here only as an adjunct to plant establishment, it is implicit that the system will be relatively portable.[7]

On the basis of the area of water broadcast, sprinkler systems may be of large, medium or small radius. These

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[7]This is subject to the exceptions where either aesthetics or risks of vandalism may dictate that the sprinkler system should be installed in-ground.

may be further classified as rotating or static mechanisms. Due to constraints of available water pressure, static mechanisms are available only for medium and small radius application.

Large radius sprinklers includes all sprinklers that wet a radius of 10 m or more under their specified range of operating pressures. Typically, they are slowly rotating mechanisms with one or more outlet nozzles. They are typically very reliable and require little maintenance. They can operate on water with only coarse mesh filtration and provide good coverage of relatively large areas with only minimal labour. However the relatively large droplet size and fast velocity of water from large sprinklers can damage new and existing growth and may cause soil compaction. Also, soils with lower infiltration rates present an increased risk of local erosion and runoff with these types of sprinklers, especially on slopes. Large radius sprinklers are still relatively inefficient as wetted areas have to be substantially overlapped to avoid gaps between arcs and to compensate for some degree of wind drift. It is also necessary to over-water the perimeter of planted areas to ensure adequate minimum application to all plants.

Sprinklers providing a wetting area radius of three to 10 m are classified as medium radius sprinklers. They may consist of rotating or static nozzles. In the former, rotation occurs either at individual nozzles, or along lines of nozzles. Rotating nozzle lines consist of metal pipe which may vary in length from 0.3 to 100 m and has outlet holes drilled radially along its length. A part of the water pressure supplied is used to rotate the pipe through a semi-circle normal to the ground surface. The resultant wetting area is rectangular, with its length depending upon the length of the pipe and its width being a function of the nozzle diameter and the available water pressure. Rotating nozzle lines of more than a few metres in length are only suitable for level runs.

Static nozzles broadcast in full-, half- or part-circle patterns. The jet of water is fragmented on an angled baffle plate (which may sometimes be adjustable) and reflected outward as a fairly fine spray. The baffle plate is sometimes radially corrugated to assist the formation of larger droplet sizes in order to increase the radius covered. Static nozzle lines consist of a length of rigid or flexible perforated pipe which distributes water along its length at different angles. As with rotating nozzle lines, they can only be successfully utilized on level runs due to total lack of pressure compensation.

In general, medium radius sprinklers are highly flexible and are ideal for general purpose irrigation. They require little maintenance and are suitable for use in automatic systems. However, as with large radius sprinklers, they are also prone to wind drift and require over-watering of the perimeters of planted areas to ensure adequate minimum application to all plants.

Small radius sprinklers wet a radius of 3 m or less. This encompasses systems often referred to as 'micro-irrigation', as well as misters and foggers. They are typically designed around a static mechanism and operate on comparatively low pressure. Sprinklers in this category are often described as a form of trickle irrigation (Bucks *et al.*, 1982), presumably on the basis of the low flow rates involved. This classification is quite erroneous as the chief advantages of trickle irrigation derive from its application of large droplets of water from a point source at or near the soil surface, a quality that none of these small radius mechanisms possess. They are sprinklers by definition as the water supply is dispersed and broadcast through the air prior to entering the ground, thereby rendering them liable to the same generic advantages and disadvantages as other sprinkler systems, albeit on a smaller scale.

Small radius sprinklers are capable of operation on low water pressure and provide more efficient water usage than larger versions as irrigation can be plant specific. They are low impact and low flow, and therefore present minimal risk of runoff and erosion problems on slopes. Their low flow rate also makes them suitable for soils with lower infiltration rates. Small radius sprinklers are ideally suited to automatic operation.

Small radius sprinklers tend to be of specialised application only as their disadvantages often render them unsuitable for general usage. Due to the fine droplet size, often a mist, particles of water take longer to fall and are therefore much more prone to wind drift, consequently evaporative losses are very high. Quite fine mesh filtering is required to avoid clogging of nozzles, hence raising both initial and maintenance costs. Foggers and misters in particular require much more maintenance than other nozzles (Bengson, 1977). Irrigation has to be sustained much longer to achieve the same depth of wetting. This entails high local humidity for prolonged periods, increasing the incidence of pest and disease attack. Small radius sprinklers often cost more to install than other forms of sprinkler irrigation due to the increased number of laterals and nozzles required and are not usually suited to large scale operations.

Trickle (Drip) Irrigation

Trickle, or drip, irrigation involves the sustained, low flow-rate delivery of drops of water at the ground surface adjacent to each plant. Since its inception (in its current form) only 20 years ago, trickle irrigation has received widespread acceptance as a viable form of irrigation, especially for dry areas. Currently, there is well in excess of 600,000 hectares of land worldwide under trickle irrigation (From data in Bucks *et al.*, 1982, p. 221). Trickle irrigation exhibits very efficient usage of water as at least 90% of the water applied reaches the root zone of the plant. Due to the slow rate of applicat-ion it is ideally suited to soils with low infiltration rates. Also it is proven effective on steep slopes in arid areas (Bengson, 1977), where water loss, runoff and erosion would otherwise pose significant problems. Deep root growth is encouraged if the flow rate is properly selected for the site soil. Studies of infiltration from a point source (Bresler *et al.*, 1971; Brandt *et al.*, 1971) have improved the system designer's ability to obtain near optimal wetted zones for each application.

Trickle irrigation can utilize water with higher salinity than other methods of irrigation, up to approxim-ately 2500 mg/l (Troeh *et al.*, 1980, p. 559). As water is applied to the soil surface, there is little or no risk of leaf burn and the action of trickle irrigation tends to leach salts outwards to the periphery of the root zone. Liquid fertilizers can be applied to plants using trickle irrigation without the risk of leaf burn and with much more accurate dosage per plant than by broadcast applicat-ion. Water application is uniform and accurately controll-able. Over-irrigation is not required to ensure adequate spread of water. This attribute also enables accurate information about the plant's water requirements to be obtained. Plant growth and yield are increased due to a more stable soil water level than is achieved by the use of sprinkler systems and weed growth is limited as water is applied only to the desired species.

Once installed, operating costs are actually quite low. Trickle is well adapted to full automatization, and the lower pressure and lower volumes of water required result in reduced pumping costs. Labour requirements can be almost eliminated through the use of automatic backwash filters and self-flushing emitters. Trickle irrigation has only a negligible effect on local humidity, as water is applied directly to the soil and evaporational losses are low. Consequently the risk of pest and disease attack is reduced in comparison to overhead watering methods. Irrigation can take place irrespective of climatic condition as it is unaffected by the wind and there is no risk of plant wilt due to foliage wetting in hot, dry weather. In areas of little or no permanent water supply, trickle irrigation is ideally suited for redistribution of harvested water during dry periods due to its low pressure, low flow rate and near maximum efficiency. Plants with different water requirements can be individually catered for on one lateral by selection of type and quantity of emitters.

The chief disadvantage of trickle systems is the high initial outlay, both in terms of labour and materials as they require more equipment and tubing than any other form of above-ground irrigation. A typical minimum component installation includes pump, fine mesh or sand filter, main lines, pressure regulators, laterals and emitters. In addition fertilizer uptake and mixing chambers may be required. If the water source used is not dedicated for irrigation, then an isolated storage tank is required. This is necessary to avoid contamination of the water supply with soil-borne micro-organisms which can enter the system through the emitters. This precaution is mandatory if the system operates on town or other domestic supply and further contributes to initial capital outlay. High quality filtration is required for trickle systems in order to reduce subsequent problems with reduced flow or clogging of emitters. Filtration needs to be well in excess of emitter manufacturers' specifications, as these do not take into account problems of gradual sedimentation of fine particulate matter. Although this further increases initial outlay, it is a cost effective action in the long term, for as Gustafson *et al.* (1974, p.19) have commented:

> one grower has two of the largest sand filters backed up by two large screen type filters. In a recent check of his orchard...he found only 11 emitters out of 30,000 not functioning.

In addition to adequate filtration, periodic flushing of the system with algacide may also be necessary. In some circumstances there is risk of wind erosion in the dry soil between emitters and between laterals (Schwab *et al.*, 1981). This is usually not significant, especially as vegetation develops. Trickle systems are not well suited to mass plantings, high density plantings and groundcovers. Expansion and contraction of polypipe laterals with temperature extremes can move emitters well away from their target plants. Length variation can easily be one m per 100 m (1%) for 12 mm polypipe laterals (writer's observation, Goulburn, New South Wales, 1983-1984). Laterals need some slack laid at regular intervals (ideally every 10 m), especially if the system is installed during hot weather.

Trickle systems are relatively easily damaged by rodents, vehicles, plant and machinery, or human error during weeding operations. Systems installed for temporary applications are not always readily reusable, especially if the demand of the new location requires the relocation or removal of a large number of emitters. It is often more feasible to salvage the emitters and use new lateral piping rather than attempting to relocate emitters as hole plugging techniques are time consuming and not always effective. The added cost of pressure-compensating emitters may be necessary on uneven terrain and steep slopes. Fill-up and drain-out times must also be considered on steep slopes as lower plants will inevitably receive additional water during these times.

Despite advances and differences in the design of individual systems, the principle of operation of trickle irrigation is fairly constant throughout. Laterals of 12mm (or sometimes 19mm) low-density polythene pipe ('polypipe') are supplied with well filtered water at relatively low pressure (typically 105 to 210kPa). Emitters are attached to the laterals at each plant, or at regular intervals, depending on the application.

Emitters are generally of a nominal flow rate of either two, four or eight litres per hour. These low flow rates are obtained by frictional losses caused by running the water through a narrow tube or passage. The different types or styles of emitters are grouped on the basis of how they achieve this flow reduction. There are three principle types of emitter in current usage: microtube, injection-moulded plastic emitters and constricted aperture emitters.

Microtube provides the simplest, cheapest and originally the most popular form of trickle irrigation. It consists of 0.75mm (approx.) diameter tubing plugged directly into laterals. Flow rate can be controlled by the length of tubing cut. However, difficulties in handling microtube, and maintenance problems associated with it, have resulted in a decline in its popularity as newer, more advanced, systems emerge.

The predominant style of emitters aside from micro-tube are two or three part, injection-moulded, plastic emitters. These are typically button or barrel shaped and have considerable handling and functional advantages over microtube systems. However, these advantages have to be offset against the higher costs of injection-moulded emitters for any given application. Due to their compact, rigid and uniform construction they are well suited to automatic and semi-automatic insertion techniques, thereby considerably reducing installation costs for large systems. Frictional flow losses are achieved much more compactly than in microtube by using a spiral channel moulded into a plastic disc or cylinder. Refinements in design have enabled incorporation of added features into these emitters, including self flushing and pressure compensating mechanisms. Insertion into laterals has been made easier, less prone to leakage and more permanent than the insertion of microtube by the use of barbed inlets, which presents a significant improvement over simple tube techniques.

In addition to the two styles of emitters described above, there are also emitters available based on a simple needle valve. These are of rigid plastic construction, and are often adjustable to vary flow rate from individual emitters. This feature may be desirable in some small-scale applications, but generally, this style of emitter is of limited use. The reduction of flow rate by aperture constriction results in a far less linear output. These particular emitters are also much more prone to clogging than the injection-moulded types due to the much finer aperture sizes and increased turbulence (writer's observation, 1980-1985).

Underground (Sub-Soil) Irrigation

Underground or sub-soil irrigation describes any means of applying water directly to the plant's roots below ground level. The obvious advantage of zero evaporation losses associated with watering underground often promotes interest in this form of irrigation. Trickle irrigation, for example, originated as an underground technique, but only became widely accepted after it was refined for use at the soil surface due to the problems inherent in sub-soil watering.

As mentioned above, the most significant advantage of sub-soil systems is the zero evaporational loss of applied water. This provides almost 100% water efficiency in terms of field losses, as well as causing little or no change to the local humidity during irrigation. Low pressure and flow rate requirements reduce outlay and maintenance costs for pumping.

Underground systems are ideally suited for encouraging deep rooting in plants as the water can be applied from below the root zone. Since they are buried, underground systems are virtually immune to physical damage from wildlife, traffic, vandalism or ultraviolet degradation. This concealment also ensures that they do not visually impair the landscape. Irrigation can be carried out irrespective of climatic condition, as it is immune to wind drift and does not wet the foliage.

Capital outlay can be significantly less than for corresponding trickle systems as water is supplied directly from laterals, which can be manufactured quite cheaply. Also, installation of sub-soil systems can be quite rapid and cheap as the pipe can be trenched, laid and buried in one operation using readily available plant.

However, unlike trickle systems, underground systems have no pressure regulatory effect and the output in l/m/hr varies widely with differing water pressure and relative height on the line. This results in a lack of ability to accurately monitor how much water each area on a line is receiving. Consequently, it is necessary to over-water in order to ensure sufficient supply.

Underground systems are almost inevitably prone to blockages, either from impurities in the water, root intrusion, or back-flow suction effects. The latter occurs when the system is turned off and the water in the pipe drains through its lowest sections, causing a mild suction in the higher sections. This draws small debris into the pipe through its outlet holes. Start-up flushing may clear the loose debris, but unfortunately there are always particles of the correct size to jam and block the holes. Because of the risk of eventual blockages, sub-soil systems are really only of merit in relatively short term applications.

Bengson (1977) found Biwall systems unsatisfactory. Because of their low pressure and spread, they only moistened narrow zones. This is especially true in soil with rapid infiltration rates, where the gravity flow of water can be considerably higher than capillary flow. As the system is buried, the only means of detecting failure is indirectly, either by plant wilting and death if the line is blocked, or by seepage if a leak occurs. Labour costs required to dig and repair, or replace sections of the pipe are high, especially as accurate information about the location of the pipes may not be available.

Since underground systems are buried, they are not reusable. This in combination with their relatively short term operational life renders underground systems inadequate for many applications. Underground irrigation also has many disadvantages in common with trickle irrigation. These include: high initial outlay; need for isolation from water supply; high quality filtration requirement; and risk of wind erosion.

Currently there are two methods of sub-soil irrigation available: perforated pipes and porous pipes. Stern (1979, p. 53) also includes water table control as a form of sub-soil irrigation. However, it is not included in this work as, firstly, it is a questionable practice that is difficult to control and can cause severe salinity problems. Secondly, it is seldom possible in dry areas because of the predominance of deep water tables.

Perforated pipes are easily the most common form of underground irrigation. They consist of smooth or corrugated, single or double walled polythene (or sometimes polyvinylchloride (PVC)) tubing with very small outlet holes placed at regular intervals along its length. These are designed to slowly release water at low pressure into the surrounding earth, which then spreads by capillarity outward from the tube in accordance with the type and texture of the soil. Double-wall tubes ('Biwall') achieve pressure and flow rate reduction in two stages. They are typically a twin-tube construction, with holes from the main tube entering the secondary tube, which then emits water into the soil.

Much experimental work has been, and is being, undertaken with porous materials such as earthenware and permeable synthetic fabric tubes. These systems are aimed at providing constant uniform wetting of the soil along their length. If a commercially viable form of porous pipe irrigation is generated from this research it may well gain popular acceptance, as it would offer many advantages over the perforated pipe systems currently available. The most significant advantage of this method is that it is much less prone to blockage of outlets than perforated pipes. Consequently it would prove more reliable than perforated pipes for long-term applications.

Control Mechanisms

The water-usage efficiency of any system of irrigation is highly dependent on the control of that system. Obvious examples of poor control undermining the potential efficiency of an irrigation system include:

(i) using sprinkler irrigation in strong winds, when field losses due to drift and evaporation would be high;

(ii) irrigating for too long on slopes with low infiltration rates, causing runoff and erosion;

(iii) irrigating unnecessarily, when soil moisture levels are too high;

(iv) irrigating too infrequently or too lightly, causing plant stress, growth retardation and soil degradation by cracking, wind erosion and scald formation.

Irrigation control mechanisms may be broadly classified into three categories according to their mode of operation: manual, semi-automatic and automatic.

In manual control of irrigation, the location, timing, frequency and duration of irrigation are all under the control of the operator. The system's efficiency is therefore dependent on the level of skill of the operator and their ability to accurately assess the field's water requirement at any given instance. Clearly time and money invested in correctly training operators is an important (although often overlooked) component of the initial outlay for a system.

In any event, manual control provides the only form of operation of irrigation systems where electric power is unavailable or unaffordable. It is ideally suited to applications where only infrequent watering is required and if labour is cheap, or already available, manual operation provides the cheapest form of irrigation control, especially in terms of capital outlay.

If operational labour is sufficiently skilled, manual control can provide system water-efficiency that equals (or exceeds) maximum expectations. It is potentially flexible and adaptable to changing conditions and presents the only alternative for portable systems that need to be moved around the areas to be irrigated.

However, in areas where labour is expensive, operating costs can be substantial. Irrigation requires the presence of labour that may otherwise not be necessary. Manual control is prone to human error and highly susceptible to unskilled labour content.

Semi-automatic irrigation control systems are systems where irrigation is commenced manually and is subsequently completed automatically. For example, irrigation may be started by pressing a switch or turning a dial. Although semi-automatic systems still require the presence of labour to initiate irrigation, they are otherwise geared towards reducing the labour content as much as possible.

Compared with manual operation, semi-automatic systems offer reduced labour content, freeing skilled staff for other duties. They are more convenient and easily regulated than manual systems and only require labour for initiation of irrigation. The quantity of water supplied to different areas can be preset, thus enabling accurate water usage control and consequently better management of water resources than would be offered by manual systems. Semi-automatic systems need not require electric power. Systems can be operated for a preset volume of water by hydraulic or mechanical mechanisms, or for a preset period by spring release mechanisms.

However, semi-automatic control mechanisms share all of the labour-related disadvantages of manual systems, albeit on a smaller scale. This is especially significant in remote areas as the presence of labour is still required to initiate irrigation.

Fully automatic systems initiate and control irrigation independent of the presence of labour. While this is clearly their major advantage, it is also potentially an area for loss of system efficiency and poor management of water resources. The difficulty lies in selecting electronically-transduceable parameters to regulate the irrigation. A skilled irrigation operator can rapidly assess the field requirement by examining the soil, inspecting the plants and observing the weather. His/her decision is also influenced by a knowledge of when irrigation or rainfall last occurred, and of the typical water requirements of the plants in the area to be irrigated.

An ideal system for automatic control would have all of this knowledge inbuilt and would have corresponding inputs for monitoring wind-speed and direction, humidity, light intensity, ambient temperature, presence or recent occurrence of rainfall as well as soil moisture content. Clearly such a complex system would be difficult to design and seldom justified. Most automatic systems currently available monitor only one or two of the following parameters: time, soil moisture, humidity, rainfall and evaporation. Of these, the vast majority are based purely on time clocks. Other types are based either on environmental input only or on a combination of temporal and environmental inputs.

The major advantages of fully-automatic control of irrigation are that maintenance costs are reduced to a minimum as no labour is required for routine operation and risk of human error causing neglect or over-watering is eliminated. Fully-automatic systems are suitable for remote sites as low power technology enables operation from solar panels or wind generators. Automatic controllers enable accurate prediction of irrigation water usage and are ideal for sites of consistent and permanent irrigation requirement. In addition, the main component parts (controllers, solenoid valves, etc.) of automatic systems are portable and reusable.

In contrast to the advantages cited above, capital outlay is considerably higher than for manual systems, electrical power is required for their operation and units still require periodic checks. Automatic time-clock systems also exhibit poor water efficiency as their timers are set for worst case climatic systems. Hence the need for some form of environmental feedback, even if only to stop irrigation during rain.

Selection of an Appropriate Irrigation System

The final selection of an irrigation and control system for a given application will be totally dependent on the physical and financial constraints imposed on the project. As an example, for a planting of trees and large shrubs, the most functionally satisfactory system might be trickle irrigation controlled by a time clock with environmental inputs. This system would provide high water usage efficiency, encourage deep rooting, be able to utilize saline water and would not require the presence of labour for routine operation. However, in the light of the project limitations, particularly the financial constraints, this system may not be feasible. Despite the various disadvantages of the systems covered, it is clear that any form of irrigation is better than none if supplemental watering is required to establish the species planted.

WINDBREAKS AND SHELTERBELTS

A windbreak or shelterbelt is a structure designed to provide wind protection for land on its leeward side (with respect to the prevailing direction of severe winds). When plants are used for windbreak construction, as is the common practice, the problems encountered in their establishment in dry areas are the same as have already been covered. The advantage of establishing windbreaks is that they provide amelioration of wind effects over a distance much larger than their height. Depending upon the design and composition of the windbreaks, this distance can be up to 30 times their height (Sturrock, 1975, p. 285). The shelter afforded by windbreaks can greatly enhance plant establishment and growth. This advantage can justify added costs for windbreak establishment, such as mulch, fertilizer and irrigation, with a view to providing longer-term savings in the cost of establishing plants in the protected area.

The degree of savings and advantages offered by windbreaks is entirely dependent upon the extent to which strong winds are a problem on the site. Therefore, the first consideration on any project is to assess the need for windbreaks by assessing the extent to which wind is a limiting factor for plant establishment and growth. Information, such as direction of prevailing and severe winds, gust strengths, temperature and humidity, should be sought from local weather stations. If this information is unavailable, or rendered invalid by local topography, then assessment must be based on site observation alone. Depending upon the scale of the project, this can range from personal observation of the site to the use of environmental monitoring equipment. Other indicators of wind strength and effect, such as microtopography and the morphology of remnant vegetation, are considered in more detail below.

Wind Effects and their Amelioration by Windbreaks

Wind is a potentially serious degrading factor for any relatively barren area, especially in hot, dry environments. It can hinder the establishment of plants through any of the following effects:

(i) increased evapotranspiration; (Skidmore *et al.*, 1969, p. 543)

(ii) mechanical damage to plants and abrasion by windborne soil;

(iii) retarded and distorted plant growth;

(iv) conveyance of undesirable substances, such as excessive dust, salt and pollutants;

(v) wind erosion.

Any landscape site evaluation should include an examination of the microtopography and remnant vegetation for any evidence of these effects. For example, the presence of aeolian soil deposits indicates potential wind hazards in the area.

On the basis of experimental data, it is generally agreed that shelter provided by windbreaks results in significantly lower evaporation rates than in open fields (Skidmore and Hagen, 1970, p. 7; Sturrock, 1975, p. 290). The only exception has been a loosely controlled experiment conducted by Blundell using evaporation tanks. On the basis of his findings he concluded that shelterbelts had no significant effect on evaporation rates in Northern England. This conclusion was generalized from experimental findings with no indication of temperatures, humidity, rainfall, dew, or even shelterbelt porosity. The results are therefore of questionable value, and certainly not suitable as a basis for generalization.

Other adverse effects of wind, such as plant damage, growth retardation and erosion, are decreased proportionately with the degree of wind reduction provided. Perhaps the most compelling evidence in favour of shelterbelts is provided by crop yield studies. Yields more than twice as great as in open fields have been measured with a 45% porous artificial windbreak (Sturrock, 1975, p. 301). Although percentage gains vary according to climates, yields in sheltered areas are always significantly higher than in open fields (*ibid.*, pp. 301-303).

Windbreak Design Considerations

Contrary to popular belief, porous windbreaks actually provide more effective wind reduction than impermeable ones. This is largely due to the turbulence and eddy currents created by an impervious barrier in the path of winds. As Skidmore and Hagen (1970, p. 363) have observed:

> at 4 *H* [*H* = height of the windbreak, in this case *H* = 2.44m] leeward of the solid windbreak, evaporation had recovered to 92% of open-field evaporation, whereas at 4 *H* leeward of 40 and 60% porous windbreaks, evaporation rates were 65 and 75% of open-field evaporation, respectively. Lowest relative evaporation over the observation region from 6 *H* windward to 12 *H* leeward was achieved with a 40% porous barrier.

These findings are of special significance in dry areas, where available soil moisture is often insufficient to support dense foliage.

The time required for a windbreak to reach optimum functioning depends on: species selected; size at planting; and prevailing climatic conditions. However, windbreaks begin to provide some degree of wind reduction from the time of planting onwards. As Miller *et al.* (1975, p. 321) have found: "the 4-year old highly permeable windbreak was already 1/3 as effective as a fully grown shelterbelt".

Windbreaks should be orientated to intercept the most severe winds to the site, and not necessarily the prevailing winds. For example, a site may have prevailing, moist, cool southerly winds with intermittent, hot, dry, gusting winds from the west. In this instance, the latter pose more of a threat to plant establishment and windbreaks should be planted with a north-south orientation (±20%).

Factors determining the placement of windbreaks include: location of the areas to be protected; site access requirements; visual requirements and other site specific constraints.

When the orientation, form and placement of the windbreak is decided, the last major consideration is the selection of the plants to be used. Beyond the obvious requirement of being able to survive and grow on the site there are several other characteristics that need to be examined when assessing the suitability of species for use in windbreaks. These are: height; density; rate of growth; life span; wood firmness; rooting habit; and resistance to disease, frost and fire (Forestry Commission of New South Wales, 1983, pp. 1-2).

It is seldom possible to find species suitable for an area that conveniently offer consistent density from ground level to apex. Therefore, windbreaks are usually designed as composite, multi-row structures. A typical configuration would have lower shrubs and small trees to the windward side with higher trees to the leeward side. This serves a dual purpose: firstly, of providing good coverage from the ground upwards; and secondly, of avoiding an abrupt rise in height, which could cause undesirable turbulence.

WEED CONTROL

Any plant growing in an undesirable location can be, and often is, considered a weed. This simple view of weeds is consistent with the definition offered by Lamp and Collet (1979, p.16) of "a plant growing in the wrong place", and provides a functional basis for consideration of weed control techniques.

The presence of weeds on a site can both visually impair the landscape as well as threaten the survival of desirable plants. The latter is chiefly caused by the unnecessary depletion of available soil water by weeds. The depletion of other resources for plant growth, such as nutrients and light, is also an undesirable result of weed infestation. In addition, weeds can foster pests and diseases[a] that subsequently attack desirable plants.

Techniques for weed control fall into three basic categories: cultivation; application of herbicides; and mulching. These techniques may be applied separately, but tend to be most effective when used in combination (Venning, 1988, pp. 30-37). Of these techniques, both cultivation and mulching offer several other benefits for plants, and are also considered in other sections of this work. In contrast, herbicides are dedicated for the purpose of weed control and are otherwise potentially harmful to the

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[a]Klingman, 1961, p.3.

environment.[9] Hence, in the writer's opinion, herbicides should be utilized with care and only applied in moderation.

Cultivation

The most familiar and direct means of cultivation used for weed control is hand-weeding. It is traditionally the method of choice for site preparation and maintenance in urban and suburban areas. Hand-weeding yields instant visual enhancement of the site and provides some measure of site weed reduction, particularly if weeds are removed prior to seeding. However it is labour intensive and is losing popularity on commercial projects, particularly over the last decade, as the cost of labour increases. Further, manual weeding has no effect on the soil weed seed bank and the process of weed removal also serves to bring new seed nearer to the surface. The weed-free period provided by hand-weeding is relatively short, as regrowth commences immediately after treatment and repeated weedings are required at two to three weekly intervals during summer.

Other, less labour intensive, forms of cultivation for weed control involve the use of mechanical implements. Consequently these techniques are usually restricted in application to the site preparation stage of the

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[9]Especially residual herbicides.

project. Where works are planned on a weed infested site, removal of the top 20 to 50 mm of soil by grading can significantly reduce weed recurrence, since a large proportion of the viable weed seed bank is in this top layer. Venning (1988, p.31) has found that this practice "significantly improves early seedling establishment", but warns against its use on heavier soils where surface glazing can occur. Also, as removal of the top soil layer may deplete the soil's nutrient reservoir, some provision should be made for subsequent fertilization and/or incorporation of organic matter (as required). Grading is one of the few forms of cultivation that provides prolonged reduction in the site weed population from a single treatment. As such, it is often the treatment of choice on sites with suitable soils and access.

Agricultural tillage techniques, such as ploughing, harrowing and rotary hoeing, are also useful tools for weed control during site preparation. However, as with hand-weeding, no residual benefit is obtained and new seeds are brought to the surface in the process. Consequently, tillage operations are usually done in conjunction with herbicide application. In the ideal instance, 'knockdown' herbicides are applied and tillage is subsequently used to dig in the weed residue and prepare the site for planting.

Herbicides

Herbicides, or weed-killing chemicals, have been extensively employed for weed control since 1944, when the selectivity of 2,4-D was first established (Klingman, 1961, pp. 10-21). The prolonged duration of their effect, their ease of application and their low cost/benefit ratio saw widespread adoption of this technology during the 1950's and 1960's. It is indicative of this period that Klingman's work, Weed Control: As a Science (1961) devotes only eight of its 400 pages to non-chemical methods. It is only since the 1970s that growing awareness of the hazards of residual herbicides (e.g. 2,4,5-T) has seen the beginnings of a decline in their popularity. More comprehensive trials and stringent controls are being introduced and several products have been restricted or removed from the market completely. However, a large selection of relatively safe[10] residual herbicides are currently available for use and Venning (1988, pp. 30-37) still advocates the prudent use of residual herbicides such as Avadex®, Treflon® or Vorox AA®. It is impossible to deny the effectiveness of these chemicals in controlling weeds and assisting plant establishment. However, in the writer's opinion, it is questionable whether the end justifies the risks involved.

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[10] 'Safe' in terms of their toxicity and half-life in the environment is always subject to the provision that label instructions are strictly followed.

The use of knockdown herbicides, such as Roundup® or Zero®, provides a less efficient but more environmentally sound approach. These substances are deactivated by the soil and thereby avoid the hazards of accumulation, leaching and pollution of waterways that are associated with residual chemicals. Also, planting can take place as close as six hours after application with no detrimental effect.[11] However, knockdown herbicides still require precautions and care in use, as even small amounts of spray drift can damage desirable plants. Used in conjunction with tillage as a part of site preparation prior to planting, knockdown herbicides provide a simple and effective means of weed control.

Mulching

One of the frequently cited advantages of mulching is weed suppression. This is by no means true for all mulches. For example, both straw and clear polyethylene mulches can exacerbate weed problems (Ashworth and Harrison, 1983, p. 181), as can fine-particle organic mulches, such as compost, manure and grass clippings. Where achieved, weed suppression is the result of placing an opaque barrier on the soil surface to prevent or retard the emergence of weeds, as well as to deprive incident weed seeds of soil

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[11]Personal communication with Mr David Rhodes, formerly of Ryde School of Horticulture.

resources for growth. Clearly weeds must be removed from the site by cultivation or herbicides, or both, prior to application of the mulch. Also, perennial weeds with bulbs, tubers, or runners, need to be eradicated prior to mulching in order to obtain the best results (Venning, 1988, p. 101).

The most effective weed control can be obtained from opaque synthetic mulches. In recent comparative trials, Ashworth and Harrison (1983, pp. 180-182) found that black polyethylene ('black plastic'), woven polypropylene fabric (e.g. Rheem Weed Stop®) and heavy-duty green plastic, were all effective in controlling weeds. Of these, the woven polypropylene is considered a better alternative to the sheets of plastic as its porosity enables water infiltration and aeration of the soil (Venning, 1988, p.101). Further, plastic sheeting is susceptible to soil and weed build-up above the sheet with time (Harris, 1983, p. 376). It is impervious to air and water, can cause runoff problems and encourages undesirable anaerobic activity, especially on heavy soils (Whitcomb, 1980, pp. 10-12). Also, the condensation effect encourages surface rooting by plants rather than the deep rooting that is more desirable in dry areas.[12]

One largely overlooked drawback of synthetic mulches is the increased difficulty and hidden costs associated

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[12]Writer's observations of black polyethylene mulches over the five-year period between 1980 and 1985.

with subsequent site maintenance. For example, plant addition or replacement is much more complicated than on sites with only loose organic mulches, and typically results in unsightly protrusions of plastic material around the site. Also, once the membrane has been disturbed, weeds that grow in the gaps formed are difficult to remove without further disrupting the membrane.

Further, all synthetic mulches share the disadvantage of being visually unpleasant and require an over-mulch, such as bark or woodchip. This is necessary to provide a more acceptable appearance, to retard ultraviolet degradation and to provide protection against wind. In view of the fact that bark mulches perform almost as well as synthetic mulches in terms of weed suppression (Ashworth and Harrison, 1983, p. 181), the added cost is seldom justified.

SITE PREPARATION AND PLANTING TECHNIQUES

Site preparation and planting cover the whole range of works requiring details and specification by the landscape architect. They form integral parts of every landscape project and provide a good platform for modifying areas of the site with low levels of available soil moisture. Assuming adequate site inspection and analysis prior to and during the design stage, the landscape architect is in a good position to highlight potential dry areas on the site. It is then possible, within the constraints of the brief, to provide some amelioration of the conditions in these areas in order to achieve higher levels of available soil moisture.

Most of the techniques covered in this section are familiar and in common use on landscape projects. The essential ingredient is in their logical utilization to solve specific site problems. These techniques are all aimed towards maximizing the levels of available soil water by reducing runoff, excess drainage and evaporation. This can be achieved by increasing infiltration rates and soil water-storage potential. Although these works are usually covered on the same details, their practical implementation is invariably staged. The sequence of events is dictated by the overall project programme unless specified otherwise by the landscape architect. Examples of the latter may be:

- All construction, plumbing and drainage works to be completed prior to planting.
- Prior to soil-mix placement and planting: site to be cleared of all builders waste and debris; existing site soil to be cultivated to a minimum depth of 200 mm.
- Exposed brickwork to be cleaned prior to planting.
- Irrigation laterals and emitters to be placed after completion of planting.

As in the examples above, a landscape architect will generally only specify sequence of events where it has direct bearing on the success of the landscape works.

Figure 3 shows a typical sequence of events for a landscape project.

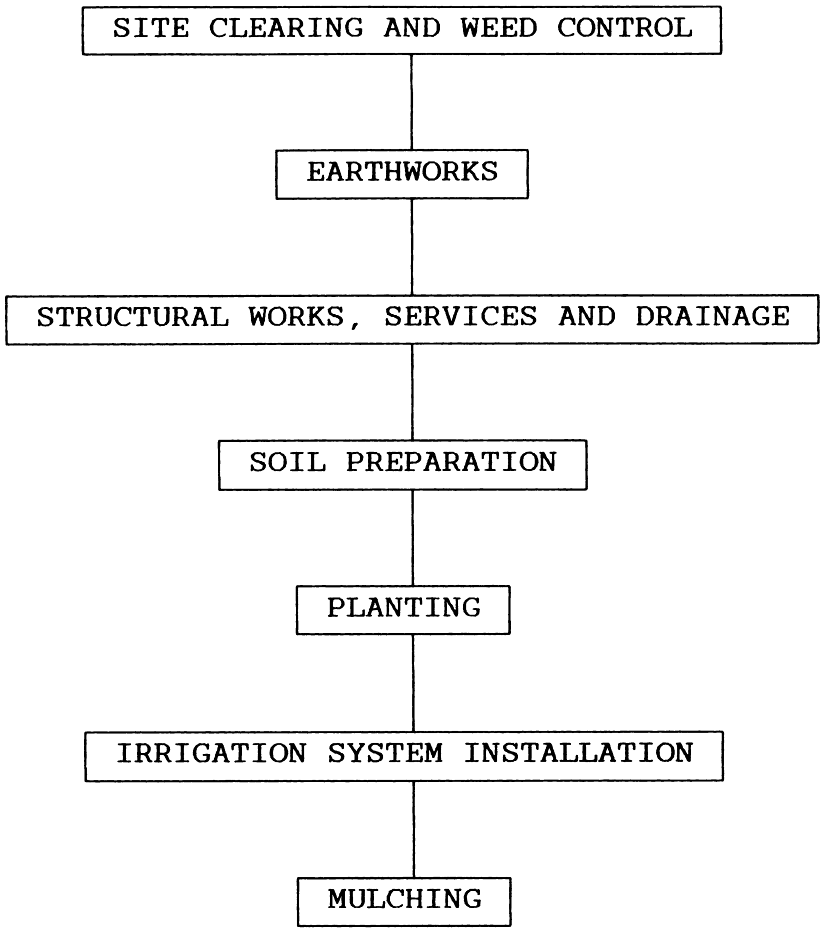

FIGURE 3: Typical sequence of events in the implementation of a landscape project.

Of the stages of implementation shown in Figure 3, weed control and irrigation have been considered in previous sections and mulching will be covered in detail in a separate section. The stages covered in this section are earthworks, structural works, soil preparation and planting. For the purpose of this thesis, these techniques are differentiated into site preparation techniques and planting techniques. 'Site preparation' is used here to denote site activities of a general nature, such as earthworks and structural works, as opposed to those techniques directly involved in the process of planting. The distinction is made purely for the purposes of this consideration and in practice these two aspects often overlap considerably. Transplanting is considered separately to planting as different sets of details are required for transplanted trees.

Site Preparation

As its name implies, site preparation is the process of preparing the site prior to planting. It includes all the earthworks and structural works completed on the site. More importantly for the context of this work, it provides the possibility of manipulating the surface and sub-surface passage of water on the site, as well as storage potentials and evaporation rates. As such, it provides the designer with an opportunity to redistribute available water on the site to best suit the needs of the proposed plantings.

Solutions for site water management are invariably design specific and are largely defined by the constraints of the brief, budget and site. However the principles involved are essentially consistent. A familiar example of the type of problem resolved by adequate site preparation is that posed by steep grades or embankments. Typically these will be among the drier areas on the site due to their high runoff/infiltration ratio. Where these grades tend upwards from the site they are predominant visual features, and their final appearance can strongly influence the overall impression of the landscape. For this reason, and also to minimize erosion, it is usually desirable to establish vegetation on these slopes.

Techniques incorporated into the design to assist the establishment of vegetation on steep grades are all aimed at reducing the velocity of runoff, providing surface storage areas and improving soil infiltration. This effect can be achieved through the use of retaining walls, ploughing of furrows along the contours, or creating overlapping pockets of earth down the slope. All of these techniques share the feature of providing level depressions for holding runon in order to enable adequate infiltration. Figures 4 to 8 inclusive show typical details of techniques useful for stabilizing and vegetating steep grades.

The creation of furrows and banks has proved an effective technique for assisting the establishment of vegetation, especially on compacted surfaces and scalds. Furrows are most effective on slopes of greater than one in 50 (Noble *et al.*, 1984, p. 178). They should be placed along contours and staggered in steep areas. Their primary function is to provide a means of water harvesting, where the spaces between the furrows act as catchment areas for the furrows. By breaking up impervious surfaces and forming banks, these furrows subsequently facilitate the retention and infiltration of the harvested water.

Furrowing serves little or no purpose on soils with good infiltration rates, such as sands, and can be counter-productive on soils with permeable crusts due to the increased erosion hazard. In both these instances, the increased water gain does not exceed the increased evaporational losses caused by furrowing, and the practice is therefore ill-advised. However, on soils with low infiltration rates, furrowing is a valuable technique. For example, in the Ord River Regeneration Project, furrowing was successfully employed to increase water retention and penetration, provide a seed bed and reduce wind velocity at ground level (Fitzgerald, 1968, p. 93). In 10 years of research at Cobar, Cunningham *et al.* (1976) found furrowing to be an extremely useful technique for assisting the establishment of vegetation by runoff management, water retention and soil temperature modulation.

Furrows may be created through the use of an opposed disc plough, often with a central ripper point if soil compaction is severe. This technique has been shown to increase infiltration rates by up to a factor of 10 (Fitzgerald, 1968, pp. 92-93).

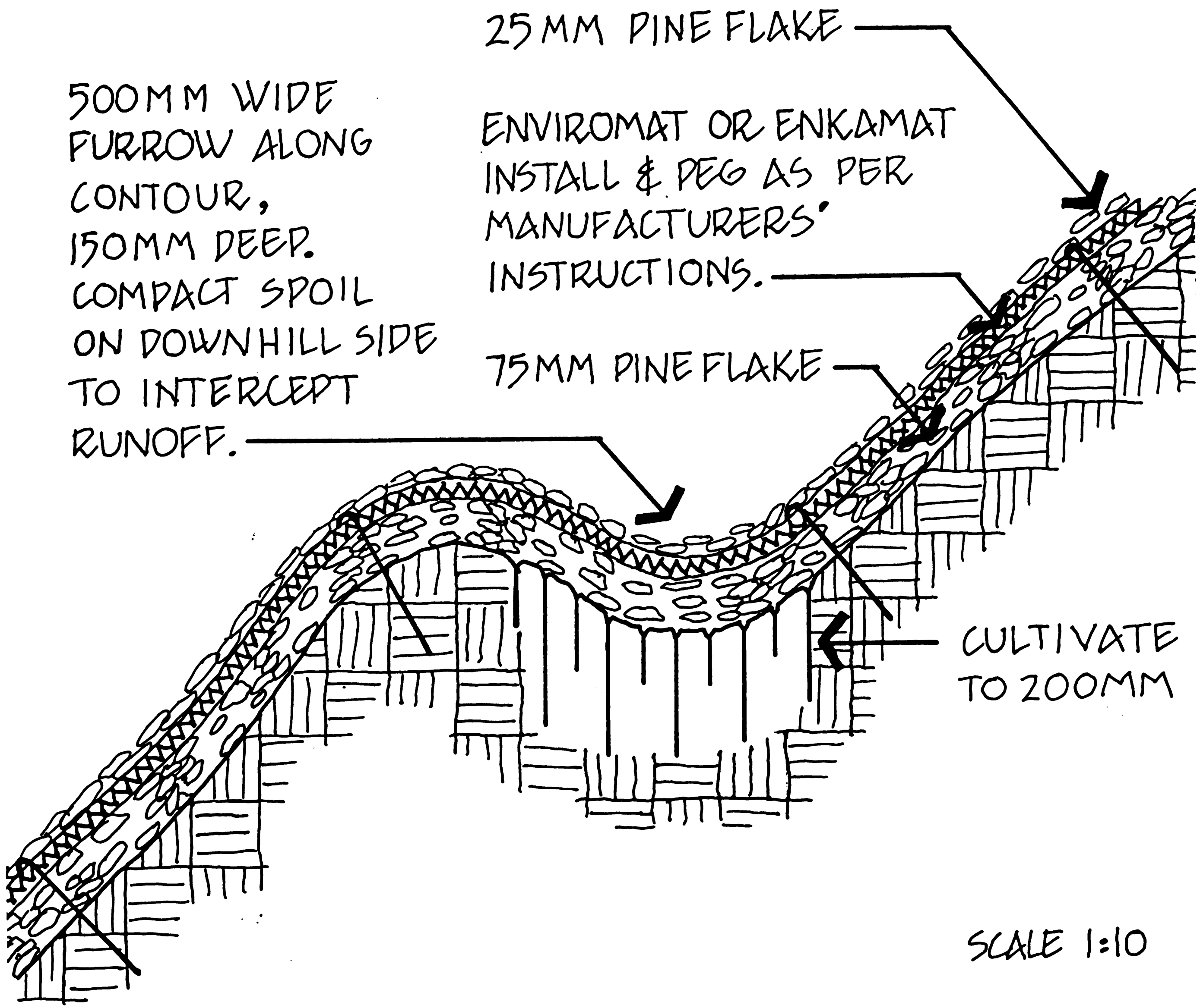

FIGURE 4: Typical Detail showing use of furrows and erosion control matting to reduce runoff losses and enhance infiltration.

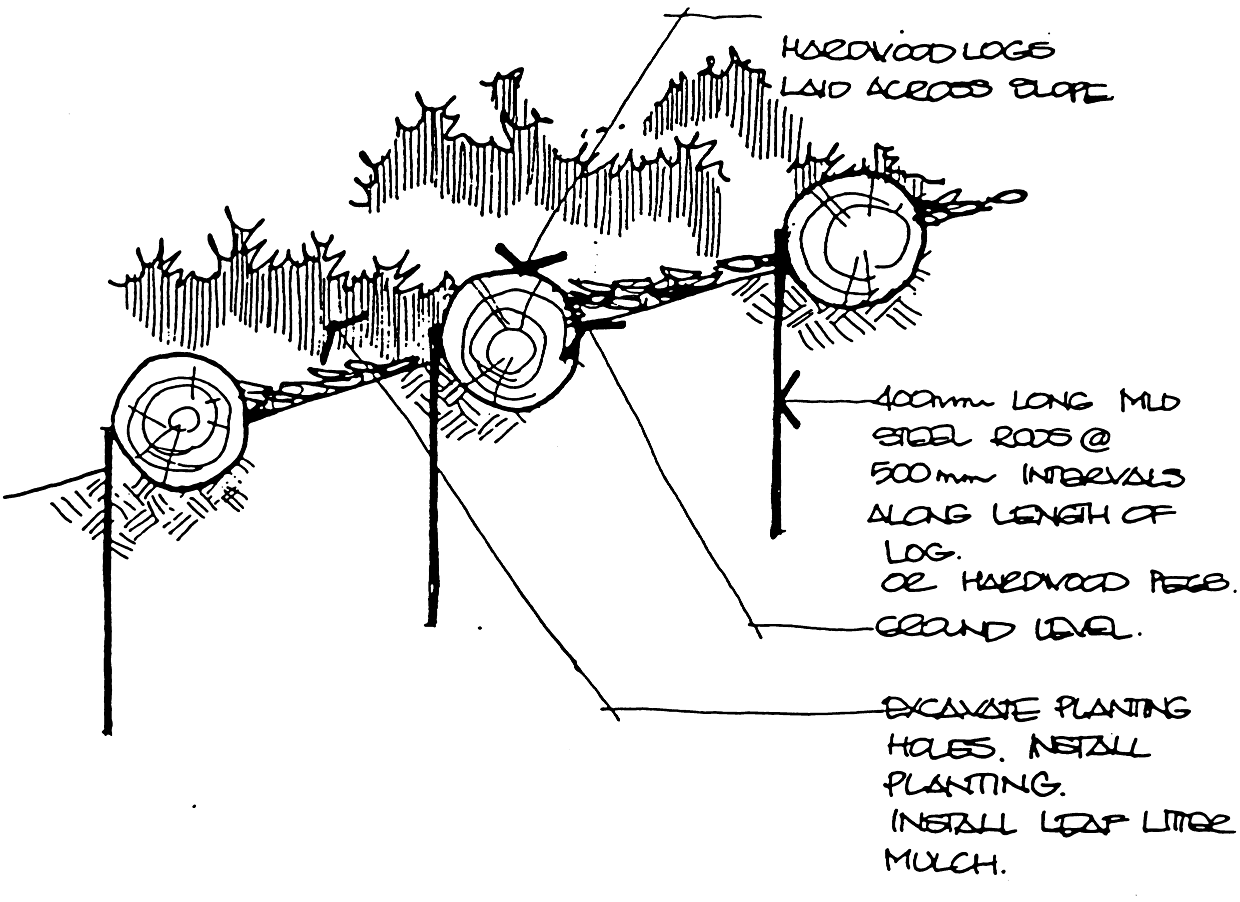

FIGURE 5: Typical Detail showing use of hardwood logs placed along the contours to reduce runoff losses. Scale: 1:10. (Detail courtesy of Stuart Pittendrigh.)

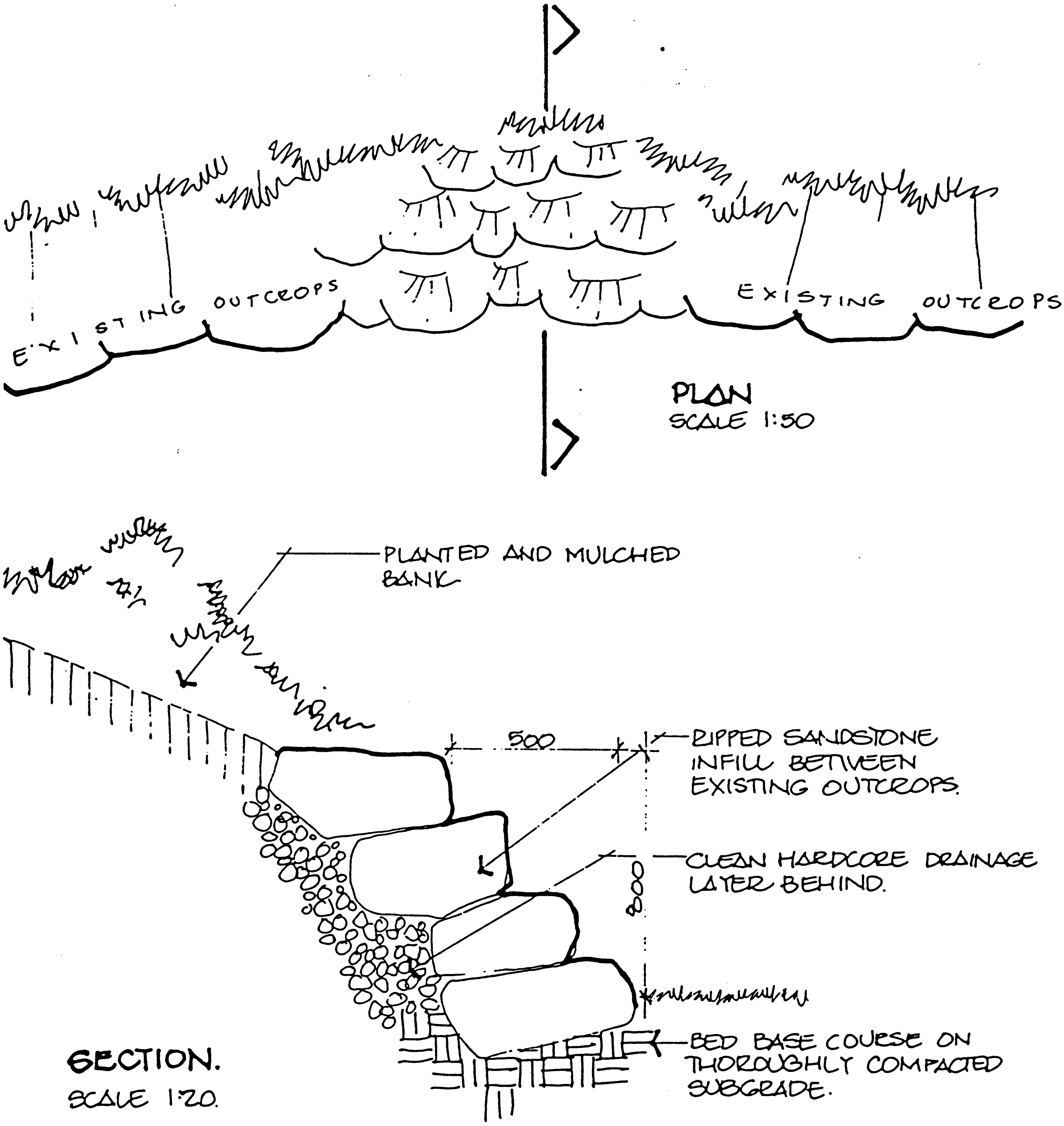

FIGURE 6: Typical Detail showing the use of ripped sandstone infill to reduce runoff losses. Scale as shown. (Detail courtesy of Stuart Pittendrigh.)

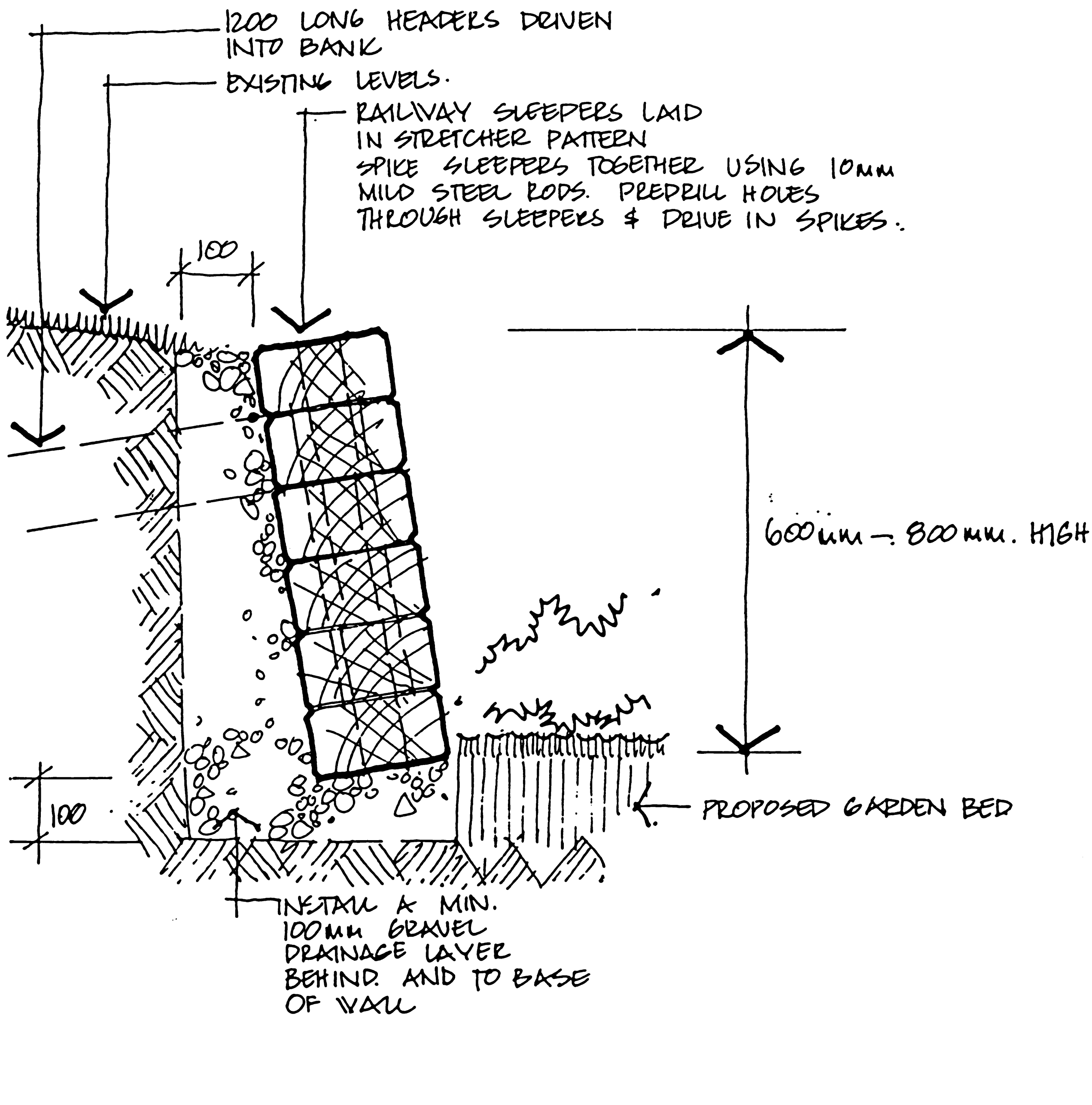

FIGURE 7: Typical Detail showing use of low sleeper walling to reduce the grade of areas to be planted. Scale: 1:10. (Detail courtesy of Stuart Pittendrigh.)

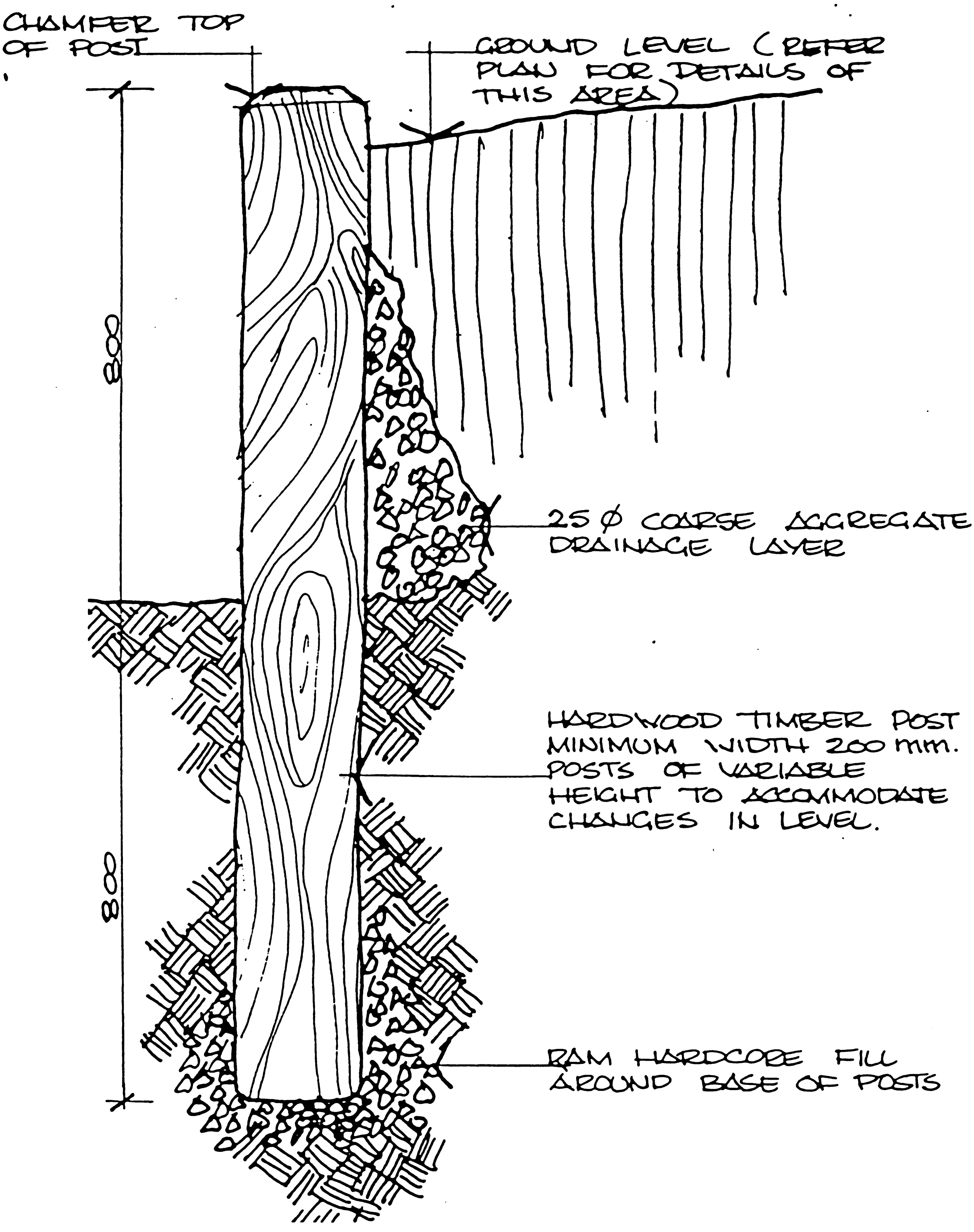

FIGURE 8: Typical Detail showing use of hardwood log walling to reduce the grade of areas to be planted. Scale: 1:10. (Detail courtesy of Stuart Pittendrigh.)

Insufficient soil depth is another commonly encountered problem on landscape projects. Two approaches are often adopted to this problem. The first is to redirect surface flow to the shallow soil and provide supplementary irrigation. The second is to add more soil in order to increase the soil water storage potential. Although the former approach can appear to yield satisfactory results, it is potentially fraught with problems. Concentrated high levels of soil water are required to buffer against evapotranspirational losses and this, in combination with the lack of soil depth, results in confined root zone development. Consequently, plants in such situations are susceptible to being blown over by strong winds as the above ground biomass increases.[13] Hence, this technique is better suited to low growing shrubs and groundcovers.

Increasing the soil depth is the preferred means of providing adequate levels of available soil water on shallow soils. This may be achieved either by relocating site soil, or by importing soil onto the site. Added soil may be uncontained, as in mounds, or contained in planters. Typical details for these two techniques are shown in Figures 9 and 10 respectively. It should be noted that mounds are more prone than planters to evaporational and runoff losses due to their higher surface area and sloped

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[13]Writer's observation of shrubs and small trees (particularly conifers) growing in shallow soils in the Sydney region.

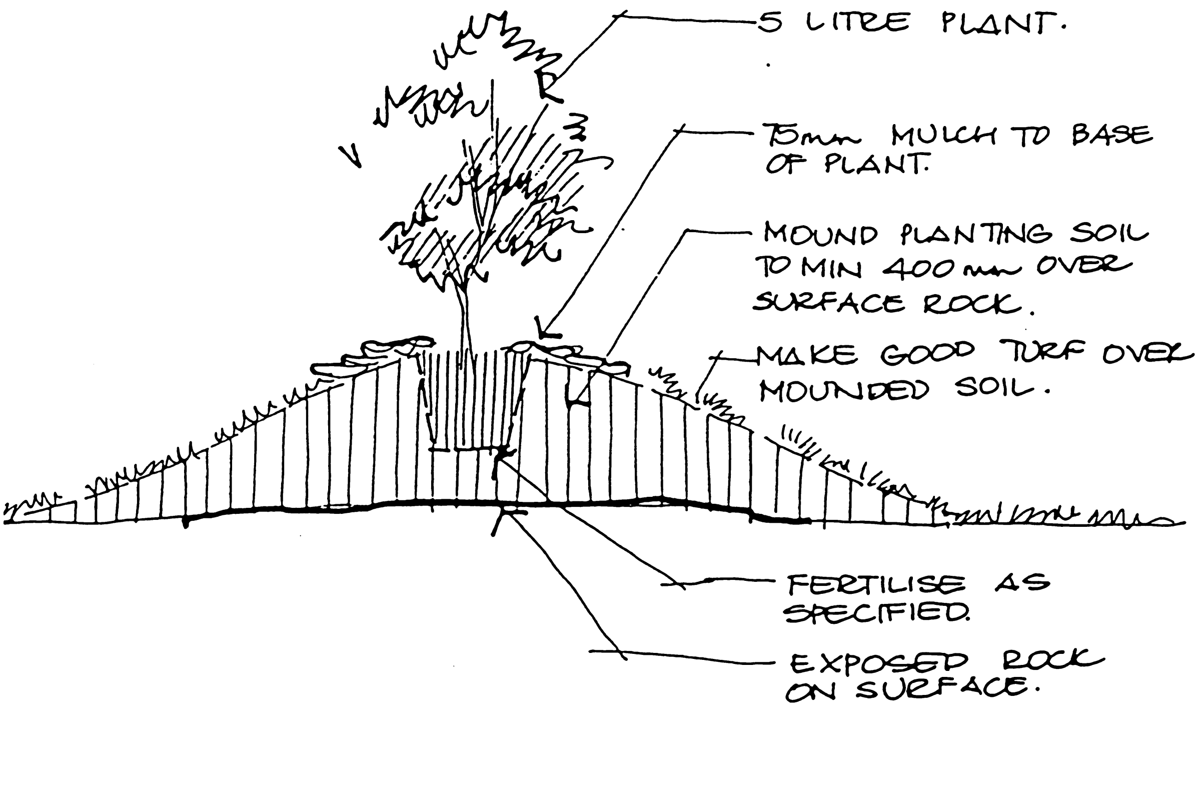

FIGURE 9: Typical Detail showing the use of mounding to provide vegetation over an exposed rock area. Scale: 1:20. (Detail courtesy of Stuart Pittendrigh.)

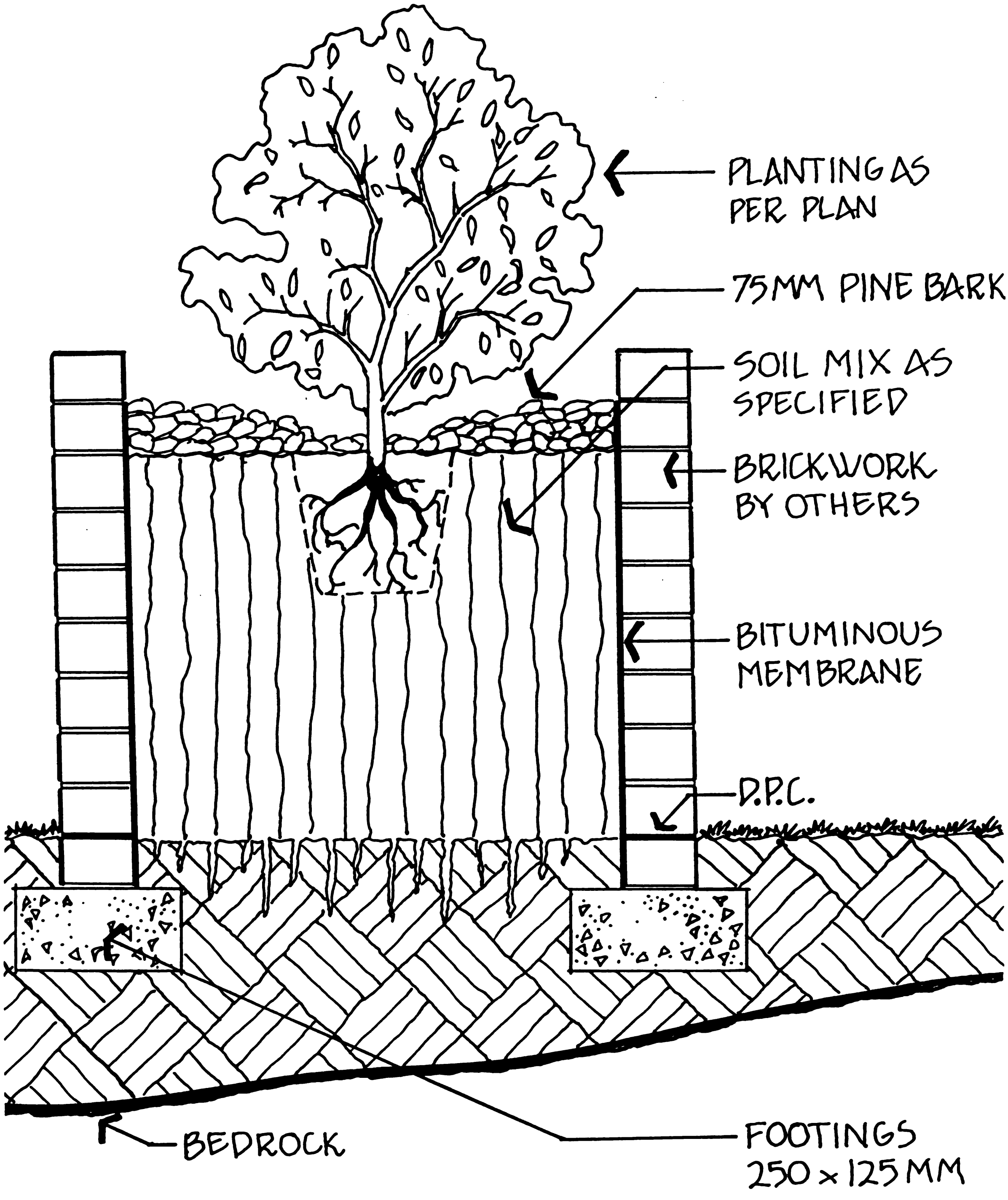

FIGURE 10: Typical Detail showing the use of a brick planter to provide adequate soil depth to support plantings. Scale: 1:10.

sides. Hence they are best suited to medium to high rainfall areas. In any event, slopes to mounds should not exceed one in three.

The successful utilization of planters is also subject to conditions. Adequate provision for drainage should be made wherever soil in planters is isolated from site soil. Drainage should include a coarse aggregate layer of 75mm minimum depth to allow relatively free-flow and levelling of water at the base of the planter. Additionally, some form of filtration is required to protect drainage routes from sedimentation. This should be fairly coarse mesh to avoid clogging by fines. Several proprietary fabrics are available for use, such as Bidim U14 Filter Fabric, and many other commonly available materials are also in use. Examples of the latter include insulation batts, shadecloth with a peat moss buffer layer, or vermiculite.

Soils with poor infiltration rates due to impervious scalds or sub-surface hardpans respond well to ripping prior to topsoil placement, planting or mulching. The major advantage of ripping soils is that infiltration rates can be increased with minimal soil surface disturbance. This helps to reduce erosion hazard in high risk areas and to minimize evaporational losses. Depending upon the equipment available, ripping may penetrate 30-40 cm deep with a heavy-duty chisel plough, or 60 cm or more with a subsoiler (Troeh *et al.*, 1980, p. 280).

Planting Techniques

When plants are first introduced into a site they are especially vulnerable to water stress. The morphology of in-ground or container grown species is substantially effected by the conditions in which the plants were grown. Most nursery plants are cultivated for rapid growth, with moisture and nutrients held at near optimum levels. The inherent problem with using these plants for dry areas on projects is that the site conditions are often incapable of supporting the existing plant morphology. At best, this results in an extended period of no growth as the plant adapts to lower water and nutrient levels. More often, such plants rapidly deteriorate and die. This adverse reaction can be avoided by careful selection of plant material. There are two options available: firstly, to plant only very young plants (seedlings and tubestock) in order to increase the chances of rapid adaptation to the new environment; and secondly, to obtain plant material that has been 'hardened-off' to suit the constraints of the proposed site. Plants in the latter category are seldom available 'off-the-shelf' and are usually only grown under contract for a specific application.

In projects where short-term results are required, neither of the above solutions may be acceptable. In such cases, the remaining option is to modify the microclimate around the plant in order to assist its adaptation to the new environment. This is achieved by supplementing the levels of moisture and nutrients available to the plant on the new site. As the level of available soil moisture is critical for plant survival in dry areas, all of the techniques examined are aimed at supplementing this level by increasing water gain to the plant.

The most direct means of increasing water infiltration and storage in the soil surrounding the plant is the use of soil additives. These are either incorporated into the site soil prior to planting, or added in a specified soil mix to be used when planting. Soil additives are primarily aimed at increasing the water holding capacity of soil around the plant rootball, thereby increasing the level of available soil water by reducing drainage losses. Additives currently in use include: compost; humus; peat; vermiculite; and super-absorbent polymers. The major potential hazard of using soil additives is the risk of confining plant roots within the additive, thereby leaving the plant prone to subsequent water stress. There are two specific precautions to be observed in order to minimize this risk:

(i) additives should never be used undiluted in the planting hole. All additives should be well mixed with site soil prior to placement in planting holes in order to minimize the root-barrier effect of abrupt changes in soil type and composition;

(ii) additives should not be concentrated near the soil surface, as this will tend to encourage shallow-rooting. Soil-additives mixes should ideally be placed below the rootball and extending for at least the same depth as the rootball (Gallacher, 1984, p. 186). This will enhance deep root penetration and consequently improve plant tolerance to periods of drought. However, this practice is uncommon and a more typical planting detail is shown in Figure 11 where media depth ranges from zero to 150 mm below the rootball.

The soil mix specified for use with planting will greatly influence the levels of available water around the rootball. Most landscape architects tend to specify from a limited range of standard mixes. In the extreme case, one mix is used almost exclusively and becomes something like a signature of the designer. A more balanced approach is to select from a list of standard mixes that are each specified as suitable for certain sets of site conditions and plantings. In terms of physical properties, a mix of fairly general application comprises three parts loam to one part organic matter. If true loam is used, the resultant mix is open, friable and of good water holding capacity. Mixes using sandy loam with added organic matter can become non-wetting in dry areas[14], and should therefore be avoided.

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[14]Writer's observation. The humus fraction of sandy loam mixes can become water repellent after only 12 months in a dry aspect.

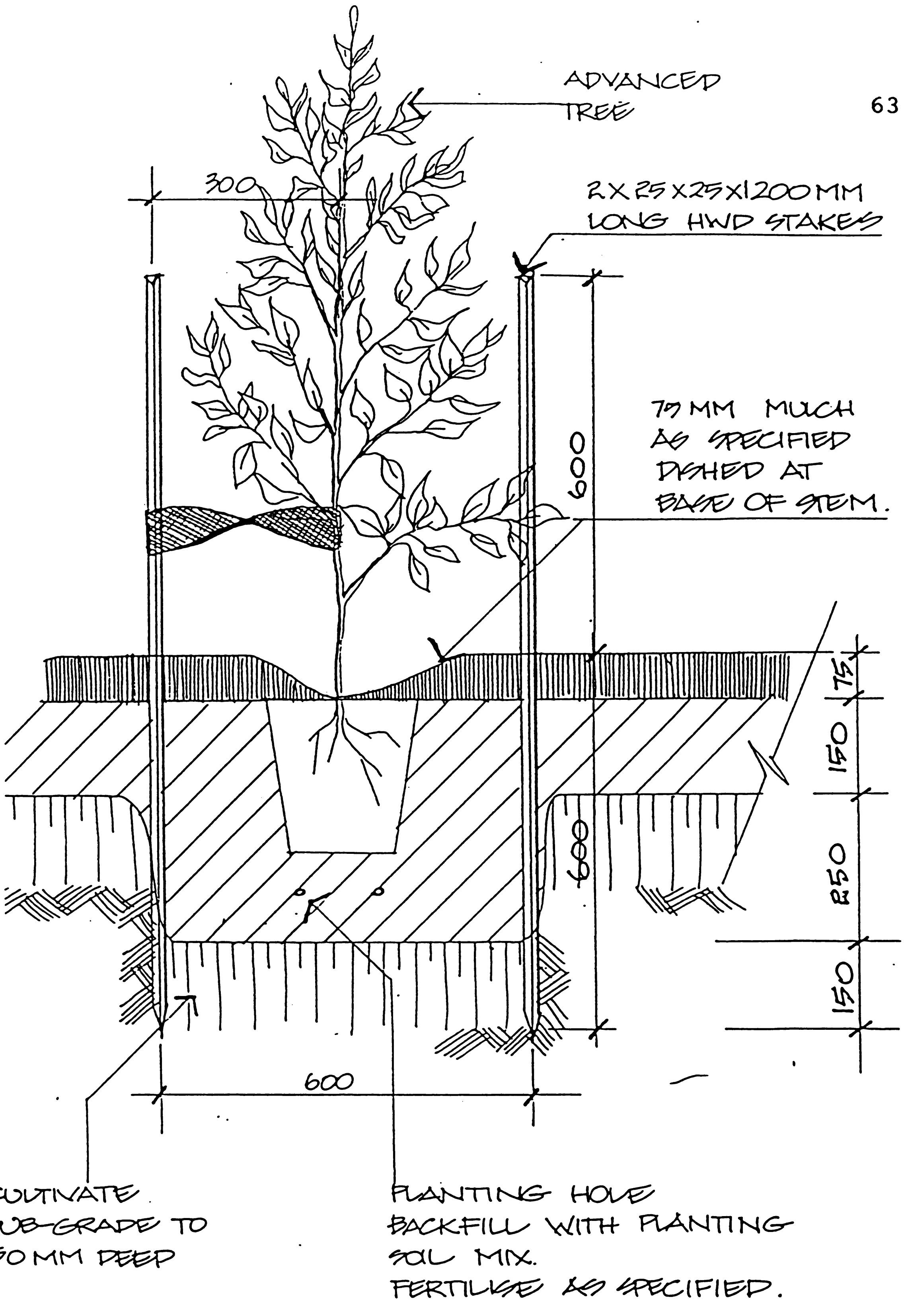

FIGURE 11: Typical Detail for planting in specified soil mix. The mix in this case comprised site topsoil and weathered hardwood sawdust in a 3:1 ratio. Scale: 1:10. (Detail courtesy of Carolyn Tallents.)

The chemical properties of the organic matter used in soil mixes can markedly influence the success of the planting. Major parameters to be considered in this regard are pH and nitrogen content. In the former case, pH of the organic matter used should correspond to the average requirements of the selected plants. For example, the commonly used mix of three parts loam to one part spent mushroom compost is alkaline. This mix can have adverse effects on acid-loving plants, such as Azaleas, Camellias and many Australian Natives.

The nitrogen content of the organic matter used in mixes is of consideration in undecomposed materials, such fresh wood shavings. Micro-organisms involved in the active decomposition of organic matter require some source of nitrogen and will cause depletion of available soil nitrogen levels if inadequate amounts are present in the mix.[15] This effect can be minimized by addition of urea and weathering of the material prior to use.

The soil surface adjacent to the plant may be modified by forming a basin around the plant in order to enhance surface storage, channel water to the plant's centre and trap run-on water for subsequent infiltration. Organic mulch may also be applied to the soil surface around the plant to supplement nutrient levels, supress

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[15]Personal communication with Judith Fakes, Ryde School of Horticulture.

weed growth, improve infiltration, decrease evaporation and reduce soil diurnal temperature ranges (Ashworth and Harrison, 1984, pp. 82-83). Inorganic mulches, such as black polythene sheeting, are not as beneficial as they provide no nutrients and increase diurnal temperature ranges in the soil (*ibid.*; Kusada, 1975).

Lengths of pipe filled with coarse aggregate may be used in conjunction with water-retaining basins to ensure infiltration to sufficient depth to encourage deep rooting. One such detail, using terra cotta agricultural pipe, is shown in Figure 12. PVC and polythene agricultural pipes are also used for the same purpose, and are less susceptible to root clogging of the outlet as they have perforations along their length.

On small-scale projects, pre-fabricated timber and black polythene condensation traps can be utilized to increase water gain and practically eliminate soil surface evaporational losses adjacent to the plant (Harris, 1983, p. 268). These traps serve the dual purpose of funnelling incident water to the plant centre as well as containing and condensing evaporating soil moisture.

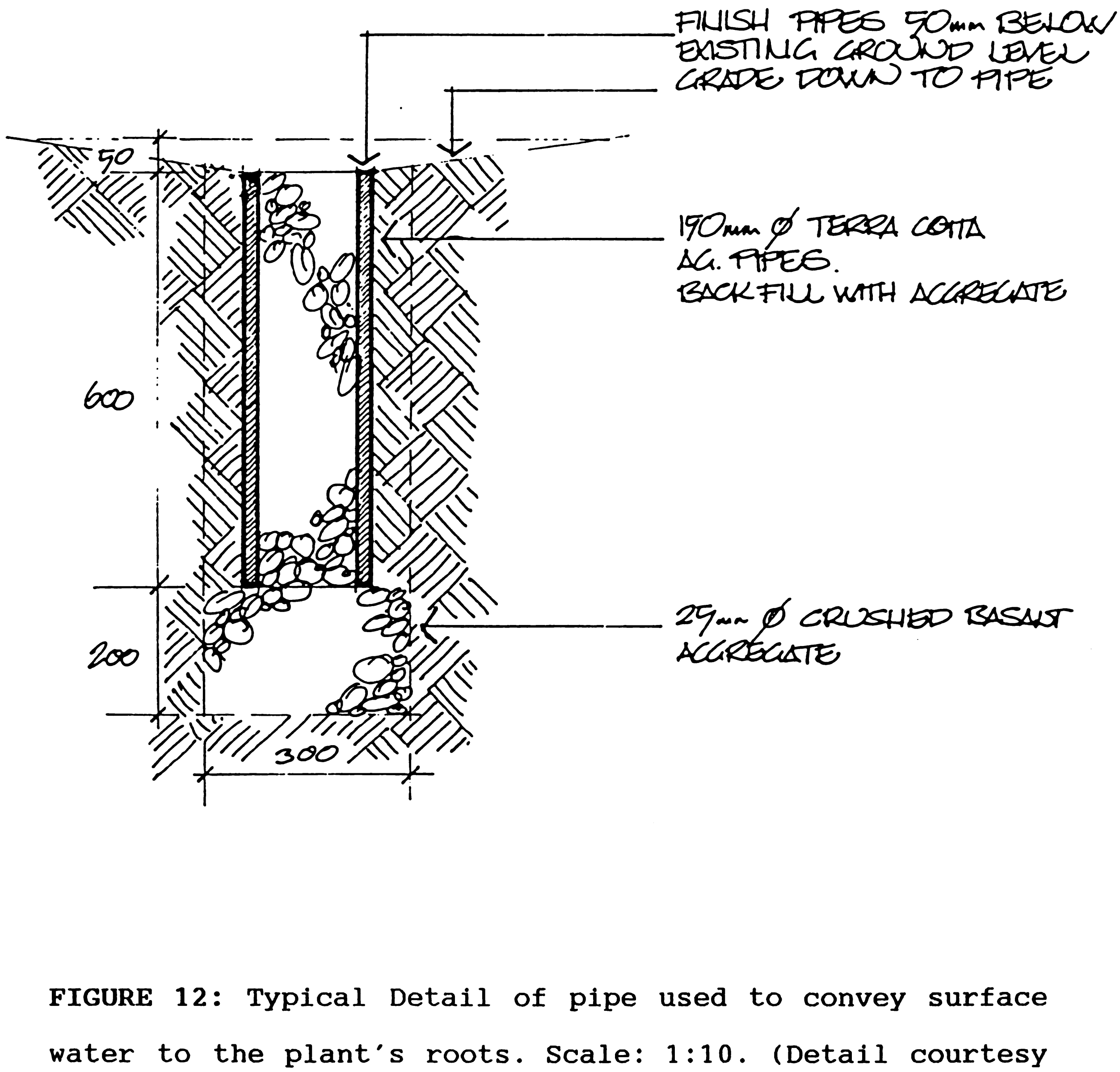

FIGURE 12: Typical Detail of pipe used to convey surface water to the plant's roots. Scale: 1:10. (Detail courtesy of Stuart Pittendrigh.)

Transplanting Techniques[16]

The increasing demand for mature specimens on landscape projects has seen an increase in the number of transplanted trees included in designs.[17] If successfully placed and established, these trees provide a sense of history and permanence in the design, especially on sites where there are no existing trees. Also, having been dug from sites where they were already established, such trees have unique character that cannot readily be replaced by uniformly grown nursery stock. Hence transplanted trees are of great significance when used in landscape projects, both in terms of their sheer presence and beauty, as well as their considerable cost.

However, transplanted trees are far more prone to complications and water stress than container-grown, or even open-ground, nursery stock. This is due both to the loss of root mass incurred through transplanting, as well as to their typically high water requirements based on their volume of foliage. Consequently such trees are more

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[16]Unless separately acknowledged, the techniques covered in this section are based on the writer's professional experience in tree transplanting (1979-1985). These techniques are fundamentally the same as those employed by Mr. Clint Bawden and other established professionals in this area.

[17]'Transplanted' is used in this section to denote trees removed from remote, often unmaintained, sites rather than in-ground nursery stock. As the latter are typically root pruned, irrigated and fertilized, their root masses are already developed in a contained space prior to removal. Their treatment and behaviour are therefore more closely aligned to those of container-grown plants.

demanding for the landscape architect and require special attention in the design, specification and implementation stages of the project.

Design stage considerations involve an assessment of the site in view of the requirements of a mature, transplanted tree. Mature specimens may be desired for visual impact, screening, shade, or any number of other functional requirements. Assuming the cost is justified, the landscape architect has then to evaluate the proposed siting of these trees. Initial evaluation is along the lines of a feasibility study. Physical constraints such as soil depth, or site access for the machinery required, may entail site modification. This can include added retaining walls, soil importation and temporary access routes. Once this task is assessed as feasible, consideration of such factors as soil type and texture, prevailing winds and availability of water may dictate further requirements in terms of guying, irrigation, and so on.

Results of these considerations provide input for the specification and planting details. These details are far more site, and even plant, specific than most. Aside from the access routes, retaining walls, guying and irrigation mentioned above, even the planting notes need to be more detailed and exacting than those for nursery grown stock. Planting holes have to be tailored to the shape and dimension of each tree's root mass and soil left lining the holes must be loose and friable to facilitate rapid root penetration into the surrounding earth. Hole depth and levels have to be assessed fairly accurately to ensure that the top of the root mass matches the site soil level and that the specimen sits plumb. Mistakes made in these two aspects can be very difficult to correct and risk damage to the specimen.

Backfilling is also a specialised requirement. Soil used for backfill should match the soil type of the root mass fairly closely to avoid soil interfaces, which can inhibit water flow and root growth. Everything possible should be done to reduce air gaps in the soil surrounding the root mass. These render ineffective roots proximal to them, effectively reducing the tree's already depleted root system.

Backfilling should be done in stages, and on no account should backfilled soil be compacted around the root mass. Compaction is often advocated to reduce air gaps, but in reality has only a minimal effect on any but the most superficial gaps and provides more dense layers of soil that tend to deflect both roots and water. Wherever possible backfill should be forced around the root mass using water under pressure. This serves the dual purpose of eliminating any air gaps and ensuring good initial saturation of the roots. If water is only available in containers, sufficient should be added to form a slurry around the root zone which can then be agitated with a tamping rod to achieve the same effect.

On completion of backfilling, a basin should be formed around the root zone and filled with a solution of Formula 20® or equivalent. This contains a mixture of rooting hormones and nutrients and is proven beneficial for transplants. Only when the tree is settled in place should any guying be rigged, as premature installation of guy lines can lead to structural stress to the tree as it settles.

Pruning, or thinning-out, of transplanted trees is best left until they are *in situ* in order to maximize their visual impact, or at least avoid it's impairment. This is with the provision that transit time from digging to planting is less than two days. In any event, excessive pruning should be avoided as the foliage is required for the production of carbohydrates necessary for root growth. Transpirational losses can be minimized by protecting the tree from full sun and desiccating winds. This may be achieved by the use of shade-cloth around the transplant for the duration of its first summer. Misting of foliage on hot days may also reduce transpiration and decrease the incidence of leaf burn by raising the local humidity around the tree. If transpirational losses appear to be a serious threat to the tree's survival, then antitranspirants should be considered as a feasible option. Antitranspirants are substances utilized to reduce these transpirational losses during the critical period following planting or transplanting. There are three principle modes of action by antitranspirants: inhibition of stomatal opening; creation of physical barriers by film-forming emulsions; and indirect action by lowering of leaf temperatures by white reflective materials (Davenport and Hagan, 1975, p. 315). The main disadvantage with the use of antitranspirants is the short-term reduction in photosynthesis. However, this is usually more than compensated for by the reduction in plant water losses during the acclimatization period.

Transplanted trees also require specialised attention during project implementation. Delivered trees should be inspected for trunk damage and to ensure the integrity of their root mass. Any protruding roots should be smoothly cut and stable in the soil mass. Loose roots with torn, jagged edges generally indicate overuse of hydraulic digging plant. Such equipment tends to pull and tear roots, both externally and within the root mass, and should only be used after root cutting is done. Supervision is also required for the planting in order to ensure that planting instructions are followed completely. Experienced transplanters may be prepared to assure successful establishment of the trees on a project management basis, whereby they oversee delivery, planting and subsequent maintenance. As these trees represent a considerable investment and require specialised attention, this is often a wise precaution.

MULCHING

Mulching is the practice of applying a layer or coating of organic, inorganic, or synthetic material (mulch) to the soil surface. The use of mulches is one of the oldest agricultural techniques (Jacks *et al.*, 1955). It is used extensively in agriculture and horticulture and is specified routinely on landscape projects. It is a simple and often highly effective means of modifying the plant microclimate and of assisting plant establishment and growth. By comparison to unmulched soils, mulches have been shown to:

(i) **decrease runoff** (Moody *et al.*, 1963, p. 700);

(ii) **increase infiltration rates** (Unger, 1975, p.244);

(iii) **increase precipitation storage efficiency** (Koshi and Fryrear, 1971, p. 820);

(iv) **decrease soil surface evaporation** (Hanks *et al.*, 1960, p. 236);

(v) **provide consistently higher soil moisture levels** (Hanks *et al.*, 1960, p. 237; De and Giri, 1978, p. 191);

(vi) **increase plant water-usage efficiency** (Agarwal and De, 1979, p.263);

(vii) **decrease nutrient leaching** (Clarkson, 1960, p. 308);

(viii) **increase nutrient levels and soil organic matter content** (Ashworth and Harrison, 1983, p. 181);

(ix) **reduce erosion** (Barnett *et al.*, 1967, pp. 83-85; Unger, 1975, pp. 246-247);

(x) reduce surface compaction of soils (Unger, 1975, pp. 243-244);

(xi) improve soil structure (Harris, 1983, p. 364);

(xii) reduce surface cracking in clay soils (*ibid.*, p.365);

(xiii) ameliorate soil salinity by increasing infiltration and reducing evaporation, thereby reducing the return of previously leached salts (*ibid.*, p.245; Heilman *et al.*, 1968, p. 280);

(xiv) increase soil-air oxygen levels (Ashworth and Harrison, 1983, p. 181);

(xv) supress weeds (*ibid.*);

(xvi) substantially modify soil temperatures (Army and Hudspeth Jnr., 1960, p. 17);

(xvii) increase and accelerate seedling emergence (Miller, 1968, p. 369; Moldenhauer, 1959, p. 39; Bengson, 1977, p. 146);

(xviii) enhance plant establishment (Dudeck *et al.*, 1970, pp. 810-813);

(xix) increase root growth and lateral spread of roots (Chaudhary and Prihar, 1974, p. 350);

(xx) increase plant uptake of Nitrogen and Phosphorus (Raghavulu and Singh, 1982, p.103);

(xxi) increase plant growth and yields (De and Giri, 1978, p. 191).

The extent to which each of these benefits is realized on a site is largely dependent on the type of mulch utilized. There is a diverse range of materials available for use as mulch. Each has different properties, and consequently different performance levels for each of the functions covered above.

Types of Mulches and Selection Criteria

Mulches can be classified, on the basis of their composition, into either organic mulches, or inorganic and synthetic mulches. These categories may be further subdivided according to the physical form of the mulch. Currently available forms of mulch include: loose mulches of discrete particles, pieces or segments; permeable sheets and woven materials; impermeable sheets; fibrous matting; and spray-on liquid emulsions. Some examples of each of these types of mulch are displayed in Table 1.

However, as agriculture has been the predominant driving force for research on mulches, visual appearance is seldom considered an issue. For this reason alone, many of the materials put forward are clearly unsuitable for use on landscape projects. For example, aluminium spray, white paint spray, roofing paper and aluminium foil (Army and Hudspeth, 1960). Others seem bizarre, even from the stand-point of agriculture, such as greenhouse glass and water in polyethylene bags (Miller, 1968, p.369).

TABLE 1

Some Available Types of Mulch Classified According to Form and Composition

FORM	COMPOSITION	
	ORGANIC	INORGANIC and SYNTHETIC
LOOSE MULCHES	chopped barks; manures; wood chip; leaf litter; wood shavings; straw; any organic byproducts	crushed stone; pebbles; e.g., river stones, volcanic scoria, blue metal; vermiculite
PERMEABLE SHEETS	woven cellulose fibres; paper-based sheets	woven polypropylene; perforated plastics
IMPERM-EABLE SHEETS	rubber sheets	clear and opaque poly-thene and PVC sheets, e.g., black plastic
FIBROUS MATTING	matting fabricated from cellulose, jute, paper, coconut husks, etc.	synthetic-fibre mats; erosion control mats; spun polypropylene mats
LIQUID EMULSIONS	hydro-mulches: straw or cellulose fibres	bitumen emulsions; paints

In contrast to agriculture, appearance is always a significant factor in the selection of mulches for landscape projects. Consideration of this aspect should not be limited to appearance at the time of placement, but should include some assessment of the probable appearance of the mulch after an elapsed period of normal site usage. For example, black plastic covered with river stones can be quite appealing when laid, but after 12 months of weeding, plant removal and replacement, pedestrian traffic and ultra-violet degradation, the end result is unsightly, and almost always requires removal within two years.

Of the forms of mulches displayed in Table 1, loose mulches are the materials most frequently used on landscape projects. In fact, they are the only type of mulches offered by many suppliers (e.g., Australian Native Landscapes). Permeable sheets, fibrous matting and hydromulches also find application on landscape projects where loose mulches alone are inadequate. For example, in dune stabilization, erosion control and bank stabilization. However, these materials are usually covered with a loose over-mulch to provide an acceptable appearance (as was shown in Figure 4).

Aside from aesthetic constraints, there are many other attributes of mulches that can affect the selection of a suitable mulch material. The weight, density and ease of handling of a mulch directly influence the costs of cartage and placement. Comparisons are possible on the basis of units of coverage. For example, to cover an area of $10m^2$ with pinebark to a depth of 75mm requires $0.75m^3$ of material. To cover the same area with plastic film requires only a small roll of 10m x 1m. However, in terms of ease of placement, pinebark may be simply cast and spread, whereas plastic films require some anchorage and are difficult to handle in windy conditions.

The durability of a mulch is a measure of its ability to withstand the degrading factors present on a site. These factors may include: micro-organisms; sunlight; wind; rain; and animal, pedestrian and vehicular traffic. Almost all sheet mulches (with the exception of woven synthetic fabrics) are susceptible to damage by pedestrian traffic and are therefore not considered durable in traffic prone areas. Spun polypropylene matting deteriorates rapidly with exposure to sunlight and should be covered in use (Ashworth and Harrison, 1983, p. 181). Organic mulches are naturally degraded by soil micro-organisms and typically require some replenishment after 12 months. Of the mulches covered in Table 1, crushed stones, pebbles and synthetic erosion control mats exhibit the highest general purpose durability.

The stability, or conversely, erodibility, of a mulch indicates to what extent it is displaced by wind, water and traffic. This is a significant consideration on steep slopes, high wind areas and access routes. Mulches that require anchorage, such as films, sheets and mats, should be assessed for their stability when anchored. The stability of loose mulches, such as wood shavings and vermiculite, can be improved by the use of cohesive emulsions (bitumen, etc.) or by using them in conjunction with erosion control mats (as was shown in Figure 4).

The permeability of a mulch to air effects the aerobic condition of the soil. Use of impermeable mulches on heavy clay soils can create anaerobic conditions and lead to soil denitrification (Whitcomb, 1980, pp. 10-12; Rickman 1979, p. 15).

Water-permeability affects infiltration rates through the mulch and, to a lesser extent, evaporational losses. In some instances, plastic sheet mulches have been found to result in lower soil moisture levels than bare earth due to their prevention of infiltration (Unger, 1975, p. 240; Harris, 1983, p.366).

Highly reflective mulches have the undesirable effect of raising temperatures around the plant foliage, resulting in increased transpiration. At the other extreme, mulches of low reflectivity, such as black plastic films, absorb a large proportion of incident radiation, resulting in substantial elevation of soil temperatures (Army and Hudspeth, 1960; Clarkson, 1960; Kusada, 1975; Gurnah and Mutea, 1982). This is a potentially useful feature in cool climates (Miller, 1968, p.369), but can prove prohibitive in warm climates. Mulches that absorb some incident light, and diffuse the balance, are more suitable for warm climates than either of the extremes cited above.

The chemical composition of a mulch dictates what substances are released during the process of its degradation. The release of plant nutrients by decomposing organic mulches is a major advantage, especially on sandy soils that are prone to nutrient leaching. However, fine-particle organic mulches (such as sawdust) can cause denitrification of the soil during decomposition (White *et al.*, 1959, p. 367). This effect can be minimized either by composting the mulch prior to application ('pre-weathering') or else by application of nitrogen fertilizer (e.g., urea) to supplement soil losses during decomposition.

Some mulches may release substances detrimental to the growth of the selected species, and this should be considered in their selection. Harris (1983, p. 372) recommends leaching or composting prior to application of bark, wood or foliage mulches that contain toxins. Examples include pine bark (Whitham, 1982, pp. 41-46) and *Eucalyptus camaldulensis* litter (del Moral and Muller, 1970, pp. 254-282). Adverse effects of toxic mulches are most pronounced with young plants, or following heavy rains (Whitham, *op. cit.*; Harris, *op. cit.*), or when mulch particles are especially fine, or mulch is over 100mm deep (*ibid.*). Mulches may also restrict plant growth by their effect on the pH level of the soil (Christensen and

McAlister, 1981, pp. 53-56). Emulsifiable bitumen/asphalt, although specified as non-toxic to plants, has been found to retard germination and seedling development in some applications (Dudeck *et al.*, 1970, p. 812; Barnett *et al.*, 1967, p. 83).

The flexibility of a mulch determines how it is affected by subsequent planting. Loose mulches exhibit high flexibility as they may be simply displaced during planting and redistributed afterwards. The procedure with sheet mulches is more complicated and usually results in damage and accelerated deterioration of the disrupted area.

The degree of flammability of the applied mulch is of major importance in fire-prone areas. The use of readily-flammable materials (e.g., leaf litter and wood shavings) in these areas is equivalent to increasing the surface fuel store and is ill-advised.

The cost and availability of mulches are often the most significant factors in determining their selection. If a material suitable for mulch is cheap and readily available, these are strong arguments for its utilization. Examples of this may include: on-site vegetation and organic residues; and locally available organic byproducts.

The requirements and constraints of any particular site and project generally dictate what properties are most important in the selection of an appropriate mulch.

These constraints may include:

(i) site location and accessibility for mulch application (in inaccessible sites, hydro-mulching may be the only feasible option);

(ii) project budget;

(iii) soil type, texture and nutrient content;

(iv) site usage, level of visibility and access requirements;

(v) environmental influences (strong winds, fire hazard, etc.);

(vi) susceptibility to erosion;

(vii) requirements of the intended and existing plants;

(viii) available resources.

Of the mulches covered, the loose organic materials tend to be the most favoured (except in high erosion risk areas). This is mostly due to their: pleasant, natural appearance; comparative ease in handling; high permeability; low reflectivity; ability to withstand pedestrian traffic; contribution of nutrients to the soil; flexibility; and ready availability (usually) at low to moderate cost. Loose inorganic materials, such as river pebbles and aggregates, are also popular. Although not offering nutrients to the soil, they share most of the other features of organic loose mulches and are exceptionally durable.

The Role of Mulches in Evaporation Reduction

The main aspect of mulches, in the context of this work, is their ability to reduce soil evaporational losses. The most direct means of reducing evaporation is to place a barrier at the soil surface to prevent escape of water vapour into the atmosphere. This can be effectively achieved by use of impermeable membranes, such as plastic sheets (Army and Hudspeth, 1960, pp. 17-22). However, impermeable plastic sheets are subject to all of the disadvantages previously covered in the section on weed control and are not recommended for use on landscape projects.[18] In contrast, the general popularity and suitability of loose mulches for landscape projects has already been covered above. Therefore, there is a real need to be able to assess and predict the relative efficiency of various loose mulches in evaporation reduction.

To arrive at some basis for recommending the most effective loose mulches for use in dry areas, it is necessary to understand the mechanisms by which evaporation reduction is achieved. Hillel (1980a, pp. 137-138) states: "in principle, the evaporation flux from the soil can be modified...by modifying the albedo...or by

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[18]With the exception of condensation traps and other applications of a localised nature. That is, when sheeting is only placed on the soil immediately surrounding the plant. This method of application negates or reduces many of the disadvantages covered.

decreasing the conductivity or diffusivity of the profile, particularly of the surface zone (e.g., tillage and mulching practices)". Modification of the soil surface albedo, can be readily obtained by use of reflective mulches. Gerard and Chambers (1967) and Stanhill (1965) have observed significant suppression of evaporation through the use of reflective soil coatings. Stanhill (1965, p.197) found that application of magnesium carbonate doubled the albedo of the soil surface and reduced maximum soil temperatures by 10°C. In terms of evaporation reduction, "The reduced soil surface temperature lowered the amount of evaporation by 20%" (*ibid.*, p. 202). These findings are consistent with those obtained by Russel (1939, pp. 65-70) for bare soil protected from the sun.[19]

However, the magnesium carbonate used by Stanhill (*op. cit.*) was for experimental purposes only, and does not represent a feasible mulch material. In practice, reflective mulches are of limited application in Landscape Architecture beyond white gravel features and can cause problems with reflected heat. What is interesting from Russel's (*op. cit.*) findings is that a 40 mm layer of straw mulch provided 40% more evaporation reduction than mere protection from sun and wind, and 57% more than bare

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[19]In an experimental isolation of the separate effects of sun, wind and mulch on water loss from columns of soil.

soil protected from the sun.[20] These findings directly connect with Hillel's requirement (quoted above) for decreased thermal diffusivity in the surface layer in order to reduce evaporative flux.

Figure 13 shows evaporation rates from a bare soil during a drying cycle. The diurnal nature of the cycle is readily apparent. It can be assumed that soil shielded from the sun would have a cycle of the same frequency but with reduced amplitude with the balance of the soil drying cycle being achieved by convective heat exchange between the surface and the air. Viewed in this light, air

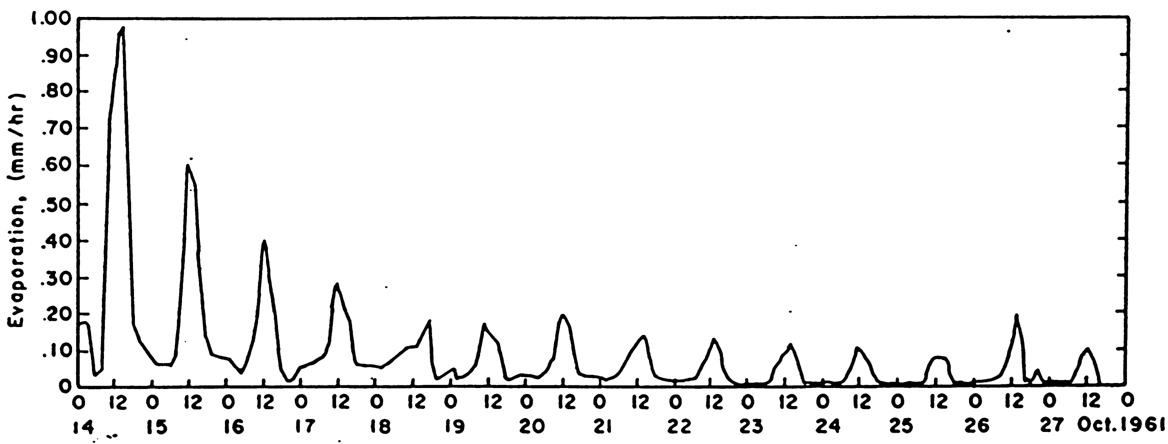

FIGURE 13: Rate of evaporation from a bare soil during a drying cycle (From Van Bavel and Reginato, 1965, in Brutsaert, 1982, p. 10).

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[20]Which is equivalent to the usage of reflective mulches to increase soil surface albedo.

temperature may seem a lesser influence on evaporation than direct insolation, yet it is quite possible to achieve accurate predictions of soil temperatures using air temperature as the sole driving mechanism (Hasfurther and Burman, 1974, pp. 78-81).

In the light of both Hillel's (*op. cit.*) comments and the foregoing, it is surprising that none of the literature[21] on the effect of insulative mulches on soil temperatures has been connected to evaporation effects. Blake (1967, p.17), in concluding his section on thermal mulches, ends with the circuitous remark that:

> all mulches reduce the variations in the temperature within the soil. [[22]] Thus, the environment of organisms that inhabit the soil, particularly those near the surface, is modified considerably. It follows that mulches can be significant in horticultural practice.

Similarly, Unger (1975, pp. 242-243) devotes a section of his work to soil temperature without any comment on its significance, whereas all other sections are related back to the practical requirements of plant growth in dry areas.

Chang (1968, p.87) at least provides detailed coverage of the significance of soil temperature when he states:

> in many instances, soil temperature is of greater ecological significance to plant life than air

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[21]At least in the works consulted by the writer.

[22]The inaccuracy of this remark has been covered in the introduction to this work.

> temperature...Soil temperatures, particularly the extremes, influence the germination of seed, the functional activity of roots, the rate and duration of plant growth, and the occurrence and severity of plant diseases.

Chang (*op. cit.*, p.98) even highlights the effects of evaporation on soil temperatures, but also fails to note the reciprocal effect of soil temperature on evaporation.

Many authors have observed and reported on the effects of loose mulches on evaporation rates without investigating the physical basis for these effects.[23] Consequently, these results are of little value except for the specific set of mulch, soil and climate that was tested. Similarly, research on the effects of mulches on soil temperature has also produced little material for performance prediction other than the rudimentary distinction between reflective and absorbent mulches (that is, high albedo versus low albedo).

Consequently, it was decided to measure the thermal diffusivity of various mulches of differing water content in order to provide some basis for predicting their efficiency in evaporation reduction. The experiments undertaken and the results obtained are detailed in Chapter II.

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[23]With the exception of Stanhill (1964, pp. 197-203) whose work was discussed above.

SUMMARY

Irrigation, windbreaks, weed control, site preparation, planting techniques and mulching have each been assessed for their effectiveness in increasing the levels of available soil water. In terms of the field water balance (shown schematically in Figure 1), each method achieves increased levels of available soil water by one or more of the following: increasing water gain; decreasing water loss; and increasing the water storage potential of the soil.

The importance of adequate site inspection and analysis is clearly identified. It is at this stage that potential dry areas can be noted, and some assessment made of their predominant causes. The functional separation of these causes into climatic factors, soil-related factors, and weed competition (as was shown in Figure 2) enables preliminary selection of suitable techniques. These techniques can then be incorporated into site-specific solutions, such as the typical details shown in Figures 4 to 12.

Mulching is the most versatile of the techniques covered and often proves to be the most cost effective. However, the diversity of materials used for mulch highlights the need for comparative data to enable material selection based on performance predictions. The experimental work detailed in the next chapter was undertaken to address this need.

CHAPTER II

EXPERIMENTAL WORK

MEASUREMENT OF THE THERMAL DIFFUSIVITY OF MULCHES

Thermal diffusivity (α) is a measure of the velocity with which heat travels through a given substance. It is defined in terms of the thermal conductivity (K), the bulk specific heat (c) and the bulk density (ρ) of the substance in question in the following relation:

$$\alpha = \frac{K}{c \cdot \rho} \quad 10^{-2} cm^2/sec \qquad ....2.1$$

Experimental work was undertaken in order to assess the thermal diffusivity of various loose mulches over a range of moisture contents. Samples of organic and inorganic loose mulches were obtained for this purpose. It was planned to assess thermal diffusivities of these mulches at their original moisture contents. Samples would then be reassessed at air-dry (following oven drying) and maximum moisture holding capacity (saturation) to obtain limits for the variation of thermal diffusivity with moisture content for each of the materials tested. If time permitted, it was intended to take readings for other moisture levels between these two limits. These values for thermal diffusivity could then be plotted against moisture content, and curves could be extrapolated to enable prediction of thermal diffusivities over a range of moisture contents. This work had already been done for a range of soils by Baggs (1986, p.240), as shown in Figure 14. It was anticipated that subsequent work by the writer, or others, would show some degree of correlation between the results obtained and the effectiveness of these mulches in supressing soil evaporational losses.

However, substantial problems were encountered in trying to accurately assess the thermal diffusivities of moist mulch materials. Consequently the time allocated for these trials was spent in efforts to establish a reliable method for calculating the thermal diffusivity of moist mulch materials. This work was seen as a necessary and important step towards the subsequent fulfilment of the original aims of the experiment.

The thermal diffusivity of a substance is generally calculated from experimental data in one of two ways. Firstly, by direct means, where α forms a part of the functional relation used[24], and secondly, by indirect means, where α is calculated from experimental results for thermal conductivity and measured specific heat and bulk density[25]. The former approach was adopted for these

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[24]Such as the method used by Jackson and Kirkham (1958).

[25]Such as the methods used by Glennie *et al.* (1979), de Vries (1952) and Kersten (1948).

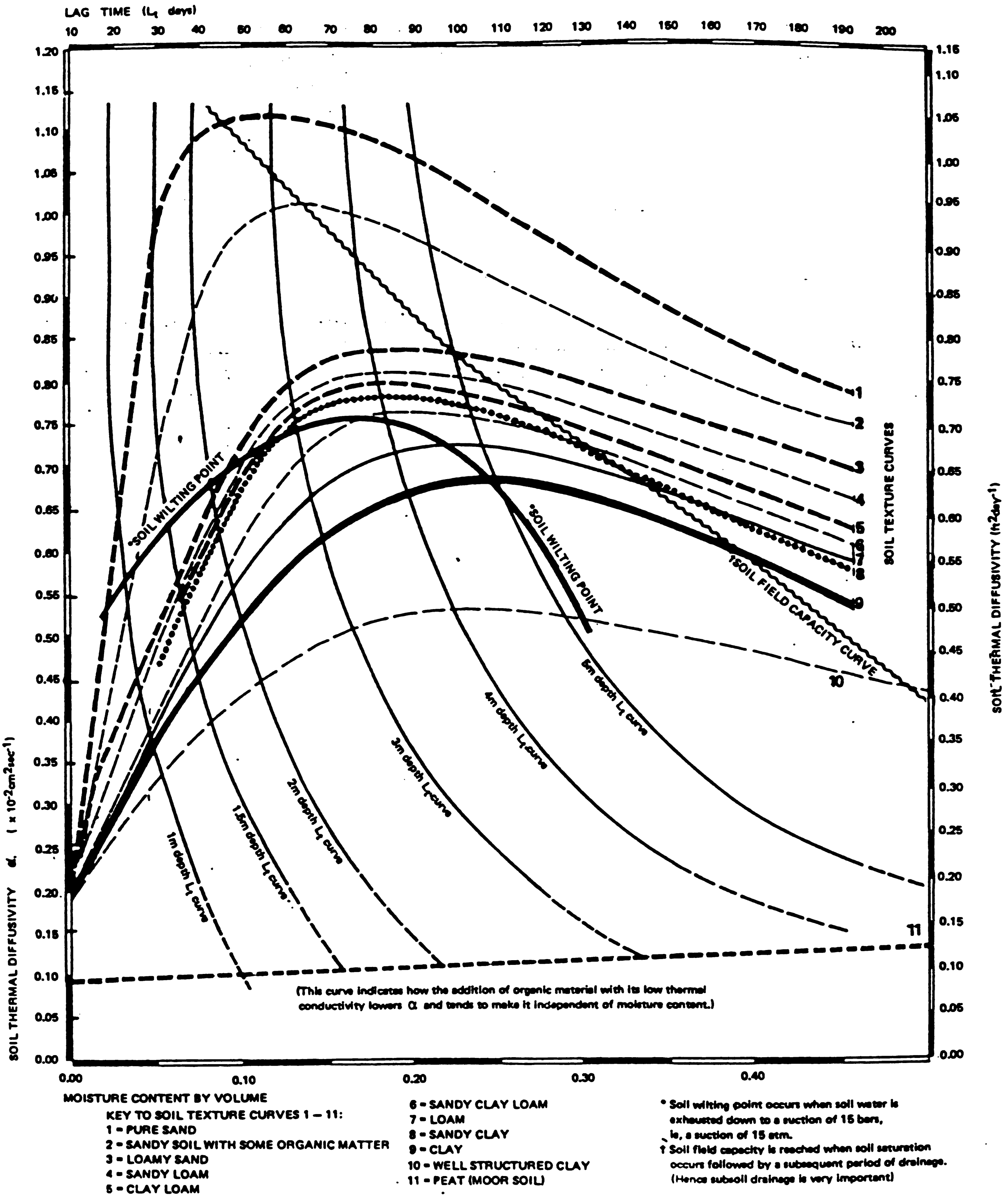

FIGURE 14: Variation in thermal diffusivity (α) as a function of soil type and moisture content (Baggs, 1986, p.240).

trials as it offered potentially less errors than the indirect means.

The experimental design was based on a set-up used by Blake (1967, p.12) to demonstrate the development of a temperature profile in a column of soil. A section through the equipment used is shown in Figure 15. Two concentric PVC cylindrical containers provided an insulated receptacle to house the mulches. The inner container was encased by a 28 mm layer of loose packed polyester fibre to provide added insulation and the cavity was sealed at the top by a sheet of 13 mm five-ply. (See Figures 16 and 17.)

Temperature sensors were initially placed at depths of 0, 5, 10, 15 and 20 cm measured vertically from the top of the column. Subsequently additional probes were located at 2.5 and 7.5 cm to provide better monitoring of the upper thermal profile in the mulch. Probes were constructed of 200 mm lengths of 8 mm O.D. PVC tubing with epoxy plugs at either end to minimize lateral heat flow.

For the purposes of analysis, the column was assumed to behave as a semi-infinite cylinder. Due to the low thermal diffusivities of the materials tested, this assumption proved reasonably valid as the lowest probe showed no significant fluctuation during the period of the trials[26].

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[26]With the exception of the wet gravel mulch, where the 200 mm probe showed a 1°C variation over the period of the readings.

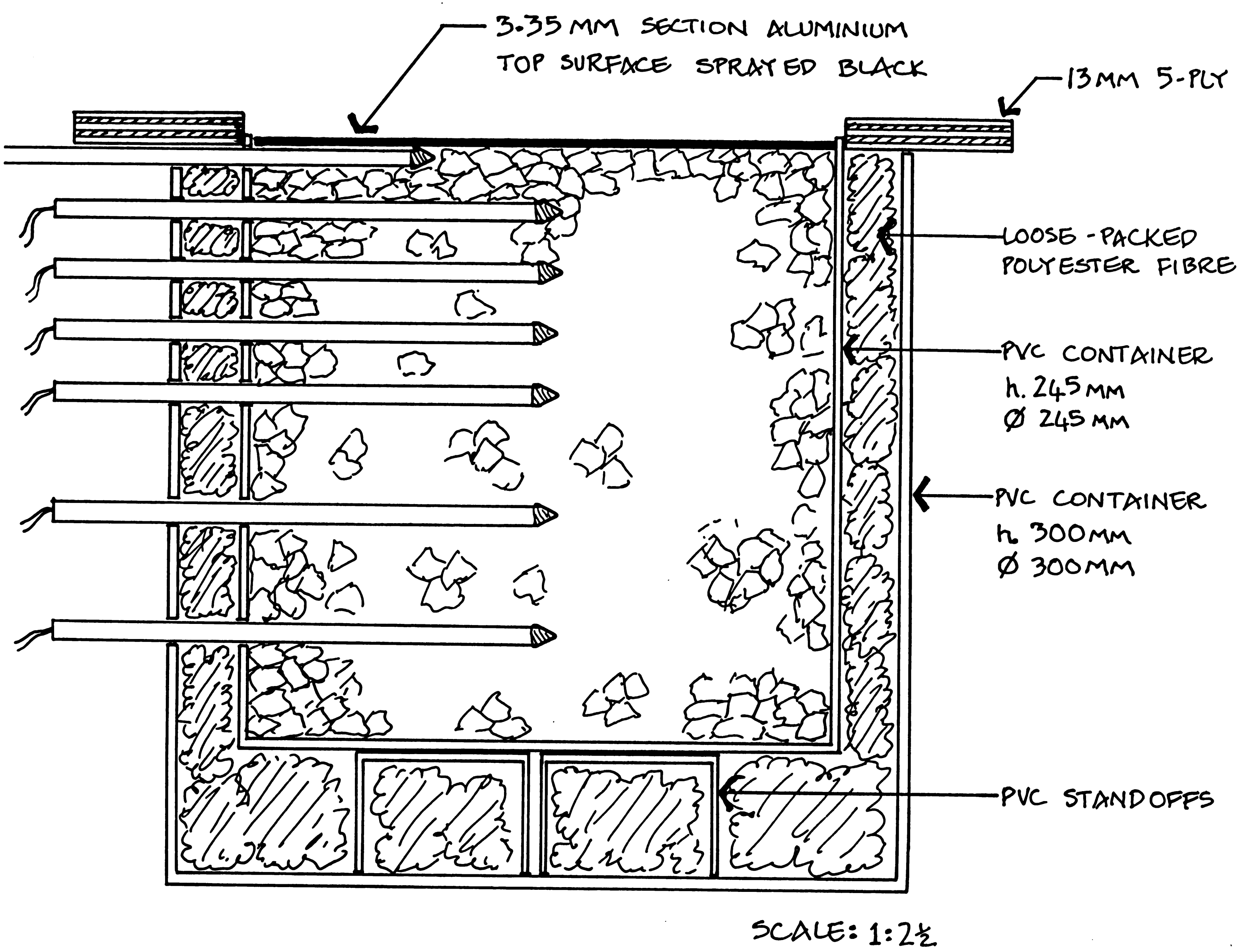

FIGURE 15: Section through the equipment used for the experiment.

The selected means for determining thermal diffusivity was to impose a constant temperature at the surface of the column. Thermal diffusivity could then be calculated using the solution for a plane source (C_1) deposited at the surface ($x=0$, $t=0$) of a semi-infinite medium whose initial concentration is C_o:

i.e., $[C-C_1]/[C_o-C_1] = \mathrm{erf}[x/2(Dt)^{1/2}]$ (Crank, 1956, p.30)

or, in the given case,

$$[T-T_i]/[T_o-T_i] = \mathrm{erf}[x/2(\alpha t)^{1/2}] \qquad \ldots.2.2$$

where T_o is the initial temperature,

T_i is the boundary temperature imposed at $x=0$, $t>0$,

T is the measured temperature at depth x, time t,

and α is the thermal diffusivity.

Equation 2.2 can be rearranged to better suit the experimental requirements,

as, $[T-T_i]/[T_o-T_i] = [T-T_i+T_o-T_o]/[T_o-T_i]$

$= 1 + [T-T_o]/[T_o-T_i]$

i.e., $1 + [T-T_o]/[T_o-T_i] = \mathrm{erf}[x/2(\alpha t)^{1/2}]$

or, $[T-T_o]/[T_i-T_o] = 1 - \mathrm{erf}[x/2(\alpha t)^{1/2}]$

but $1 - \mathrm{erf}[x/2(\alpha t)^{1/2}] = \mathrm{erfc}[x/2(\alpha t)^{1/2}]$

therefore,

$$[T-T_o]/[T_i-T_o] = \mathrm{erfc}[x/2(\alpha t)^{1/2}] \qquad \ldots.2.3$$

The expression $[T-T_o]/[T_i-T_o]$ represents the normalized temperature, or the ratio of the temperature increase at depth x, time t, to the imposed increase at $x=0$, $t=0$. Hence, when $[T-T_o]/[T_i-T_o]$ is measured at depth x, time t, a value for the thermal diffusivity (α) can be derived

FIGURE 16: View of the equipment used for the experiment following the placement of the wood chip mulch.

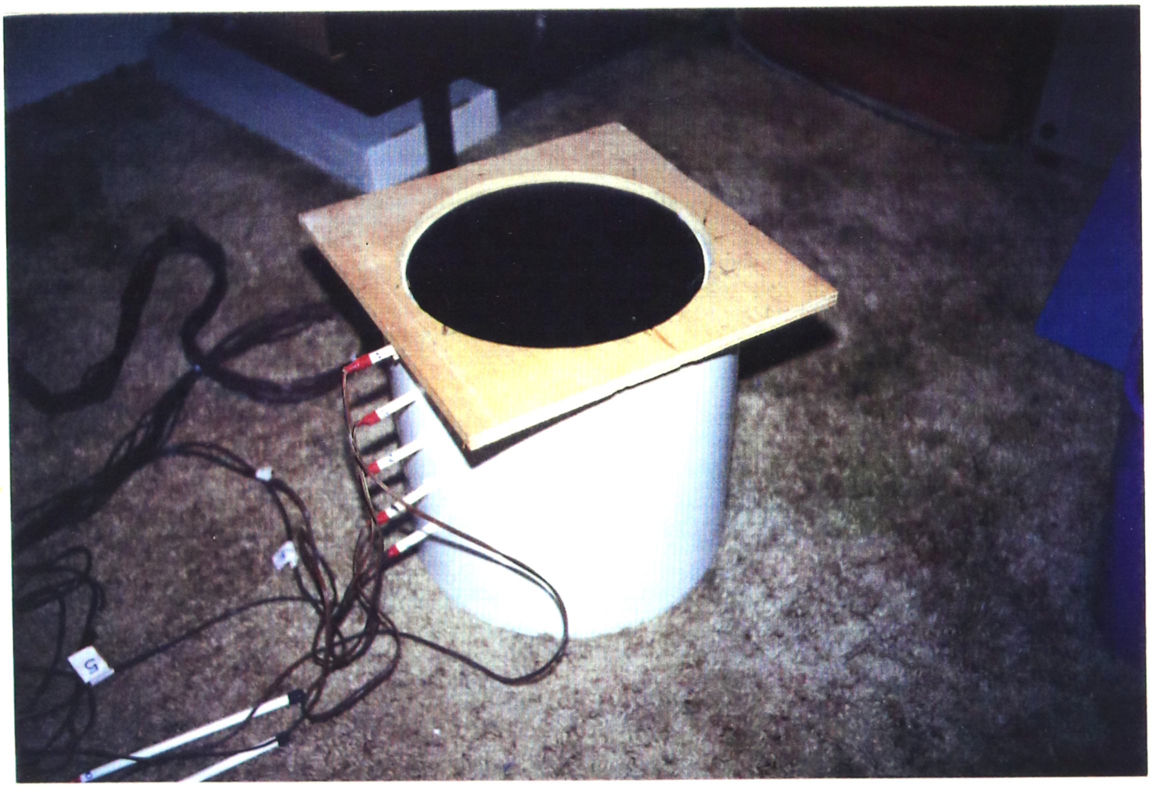

FIGURE 17: View of the equipment used with the ply-wood and aluminium disc in place.

from the error function (erfc) curve shown in Figure 18.

This method of analysis was used to assess the thermal diffusivity of wood chip (red gum) mulch. The results obtained are shown in Figure 19 and Table 2.

TABLE 2

Calculated Thermal Diffusivities at Depth x = 5cm Using the Linear Flow Model for Moist Wood Chip

Elapsed Time (minutes)	Thermal Diffusivity (α) ($\times 10^{-2}$ cm^2/sec)
81	0.117
169	0.096
324	0.076

The column of wood chip mulch was allowed to equilibrate to a value of T_o = 24°C. A boundary temperature of 75°C was then applied to the surface at time t = 0. This was achieved by pre-heating a 3.35mm section extruded aluminium disc and then maintaining its temperature by an infra-red lamp placed 340mm above the disc.

The thermal diffusivity values obtained (see Table 2) were smaller than anticipated. This was attributed to cooling of the disc on initial contact with the mulch resulting in a lower effective boundary temperature prior to the system reaching steady state (approx. 25mins.).

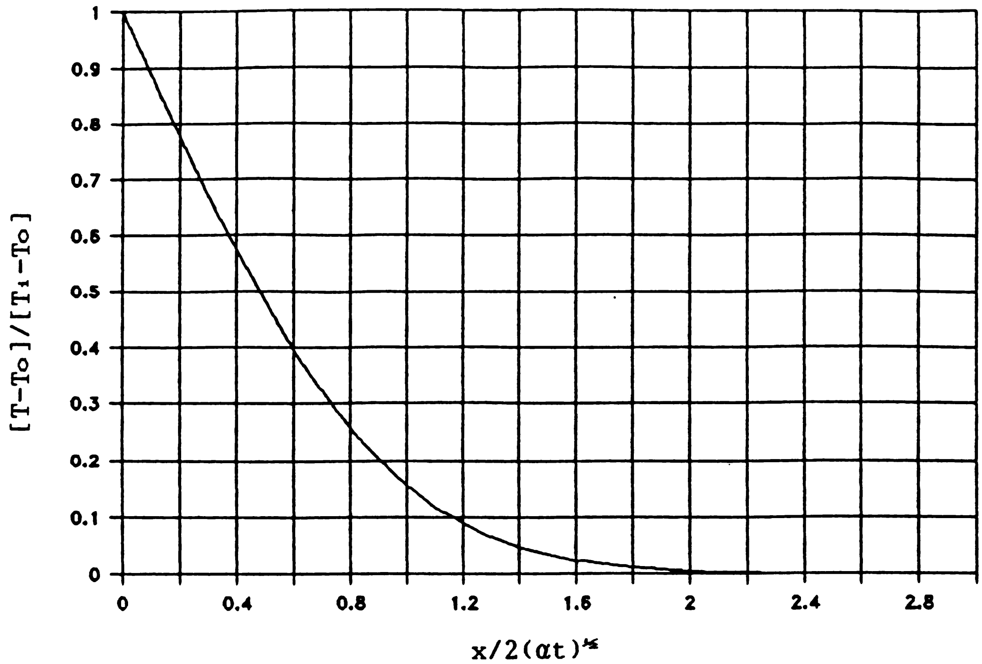

FIGURE 18: Plot of error function values for $x/2(\alpha t)^{½}$ (From data in Crank, 1956, p.326).

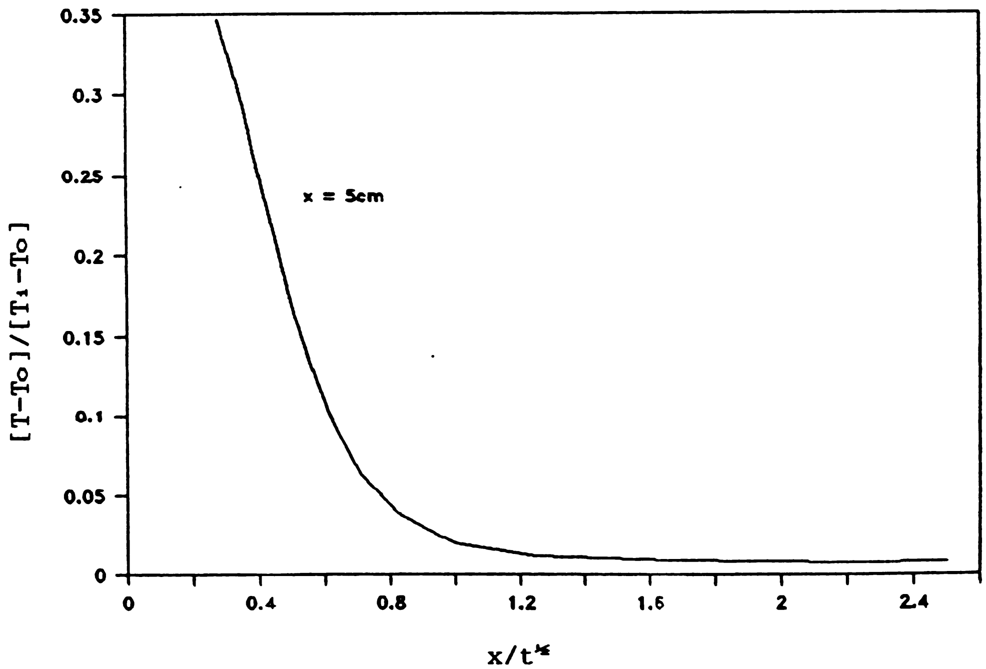

FIGURE 19: Results obtained for $[T-T_o]/[T_i-T_o]$ versus $x/t^{½}$ cm/min^{½} for moist wood chip (moisture content 17% w/v).

The decreasing thermal diffusivities (see Table 2) for the mulch at 5cm deep were accounted for by drying of the mulch profile caused by the heat applied. This technique for determining thermal diffusivity was therefore considered unsuitable for use with moist materials as no accurate measurement of the moisture contents of the mulch during this drying period could be obtained. Although the variations obtained due to drying were relatively small in this case, it was expected, on the basis of data shown in Figure 14, that they would be much more significant for inorganic materials. Also, the non-linear heat transfer effects due to vapour flow could significantly impair the accuracy of the findings. For these reasons a different approach was sought.

Jackson and Kirkham (1958) had avoided these problems in moist soils by using an alternating heat source at different (decreasing) periods of oscillation. The non-linear aspects of heat transfer were minimized by plotting the resultant values for diffusivity against the decreasing period, and consequently the decreasing thermal gradient (δT). The curves obtained were then extrapolated to period, $P=0$ ($\delta T=0$). The thermal diffusivities of the soils tested were computed from the lag times through the relation:

$$\alpha = P/4\pi \cdot (\delta x)^2/(\delta t)^2 \qquad \ldots .2.4$$

(adapted from Jackson and Kirkham, 1958, p. 480)

where α = thermal diffusivity,

P = period of the alternating temperature applied,

δt = lag time over distance δx.

The results obtained were termed "apparent" thermal diffusivities by Jackson and Kirkham (*ibid.* p.479) to distinguish them from the values obtained by extrapolation, which they termed "real" diffusivities.

Several trials were made to assess the suitability of Jackson and Kirkham's method for use with moist mulch materials, and to adjust the range of experimental parameters to suit the different properties of mulches. Mulches differ significantly from the soils and sand tested by Jackson and Kirkham (*ibid.*) in particle size, porosity, and diffusivity. Because of the typically large and irregular size and shape of mulches, and their high porosity, probes could not yield reliable results any higher than 2.5cm in the column. For the same reasons, the probes could not readily be inserted as close together as was possible in soil. Also the lower diffusivities of the organic mulches meant that applied temperature variations were very rapidly damped to $\delta T=0$ within the material.

Three mulch materials were used for these trials: Red Gum wood chip; pine flake; and red river gravel. The measured properties of each of these materials is shown in Table 3. As the mulches were stored in the shade in sealed plastic bags and rolled daily, moisture content was assumed constant throughout each sample.

Several methods for boundary temperature modulation were tried, including alternating hot and cold water, infra-red heating, and fan-forced cooling. The method adopted consisted of alternating between application of the infra-red lamp and an ice water bath. This provided sufficient amplitude (30°C at P=120mins) to achieve reliable readings in the organic mulches. Even with this considerable temperature fluctuation, only the probe at 5cms showed significant modulation in response to the applied heat cycle (See Figure 20). Hence, two additional probes were placed in the upper profile, one at 2.5cm and the other at 7.5cm, to provide some replication.

TABLE 3

Properties of the Mulches Used in the Trials

	Red Gum Wood Chip	Pine Flake	Red River Gravel
PARTICLE SIZE (mm)	100x50x25 to slivers & fibres	35x35x15 chunks, 100x3x5 slivers	9mm diam. average
MOISTURE CONTENT:			
appearance...........	moist	moist	wet
by mass..............	46%	50%	3%
by volume............	16%	9%	6%
POROSITY (f)	0.67	0.75	0.54
BULK DENSITY (ρ g/cm^3)			
wet mulch............	0.5	0.28	1.85
air-dry mulch........	0.31	0.18	1.79

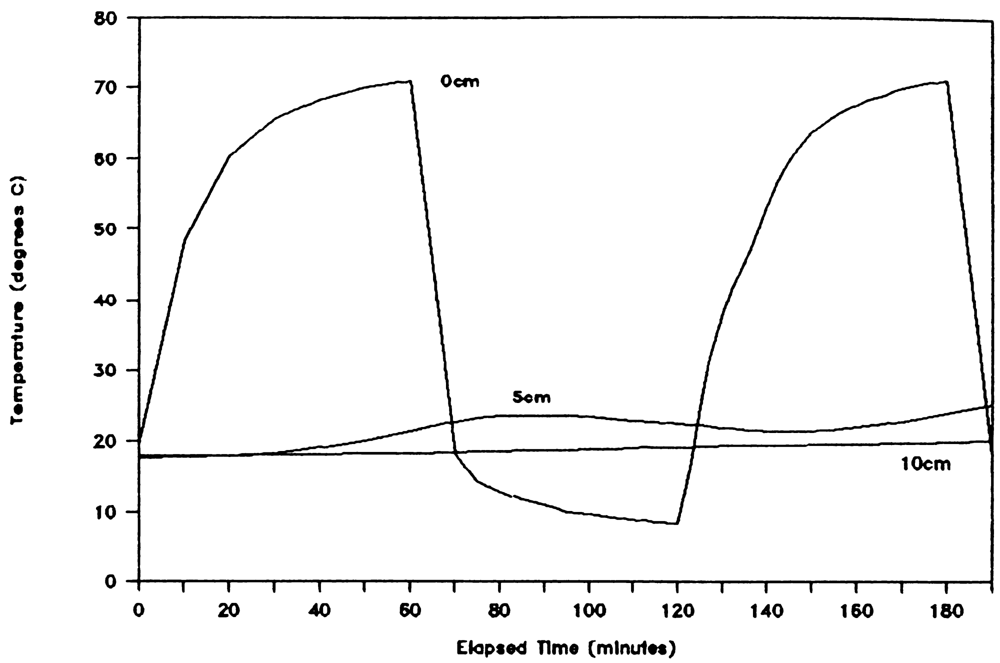

FIGURE 20: Readings for wood chip taken prior to the addition of probes at 2.5cm and 7.5cm. (P=120mins.)

Readings were taken for the pine flake mulch for four applied periods of temperature fluctuation: 120, 60, 30 and 20 minutes. Results for the 120 and 20 minute periods are shown in Figures 21 and 22 respectively and provide an indication of the reduction of thermal gradient achieved by reducing the period of the applied heat cycle. Time lags were measured relative to the surface probe, and apparent diffusivities were calculated using the relation (Equation 2.4) provided. These figures are shown in Table 4. The computed values for α were then plotted against the period, and a curve was then fitted and extrapolated, as shown in Figure 23.

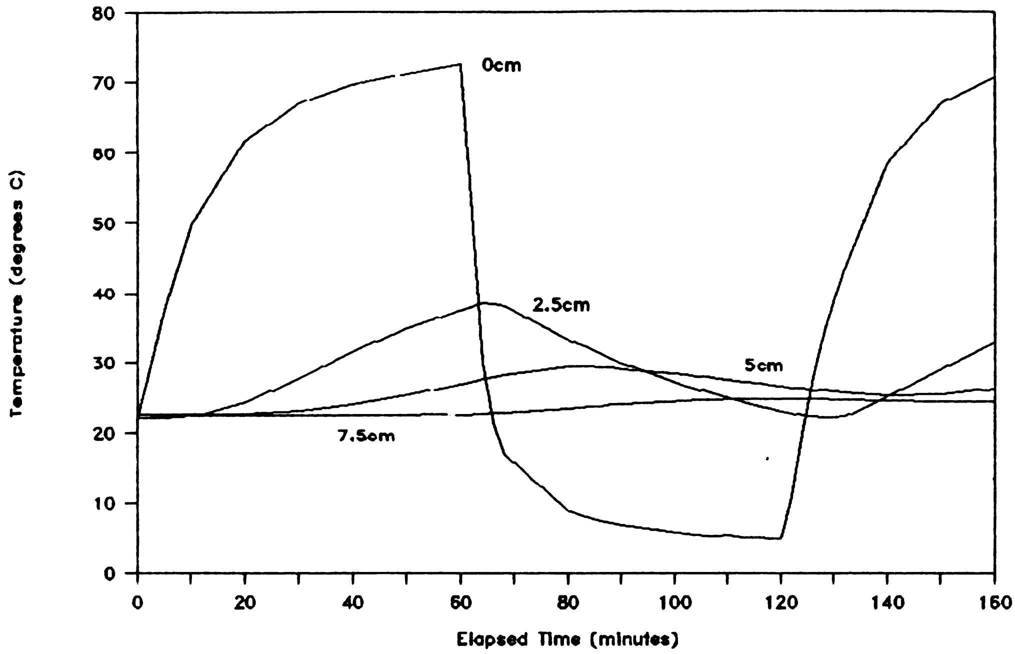

FIGURE 21: Temperature readings taken for the pine flake mulch at applied period, P = 120 minutes.

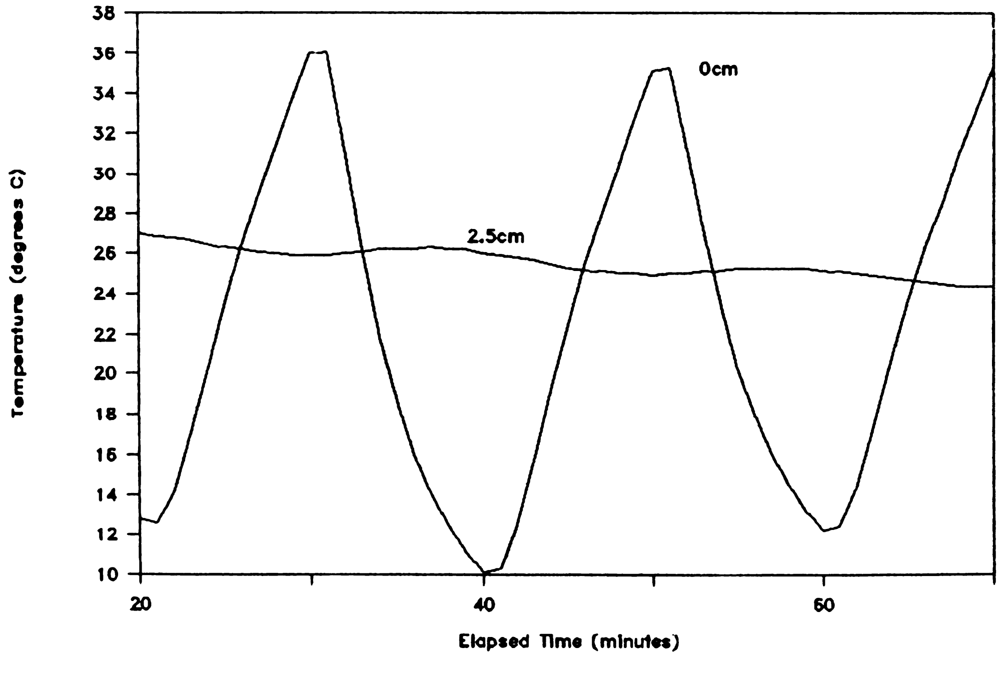

FIGURE 22: Temperature readings taken for the pine flake mulch at applied period, P = 20 minutes.

TABLE 4

Apparent Thermal Diffusivities at Depth x = 2.5cm,

for Pine Flake Mulch

Applied Period (P mins.)	Measured Time Lag (δt mins.)	Thermal Diffusivity (α) (x 10^{-2} cm^2/sec)
120	7	2.0
60	10	0.61
30	10	0.25
20	9	0.2

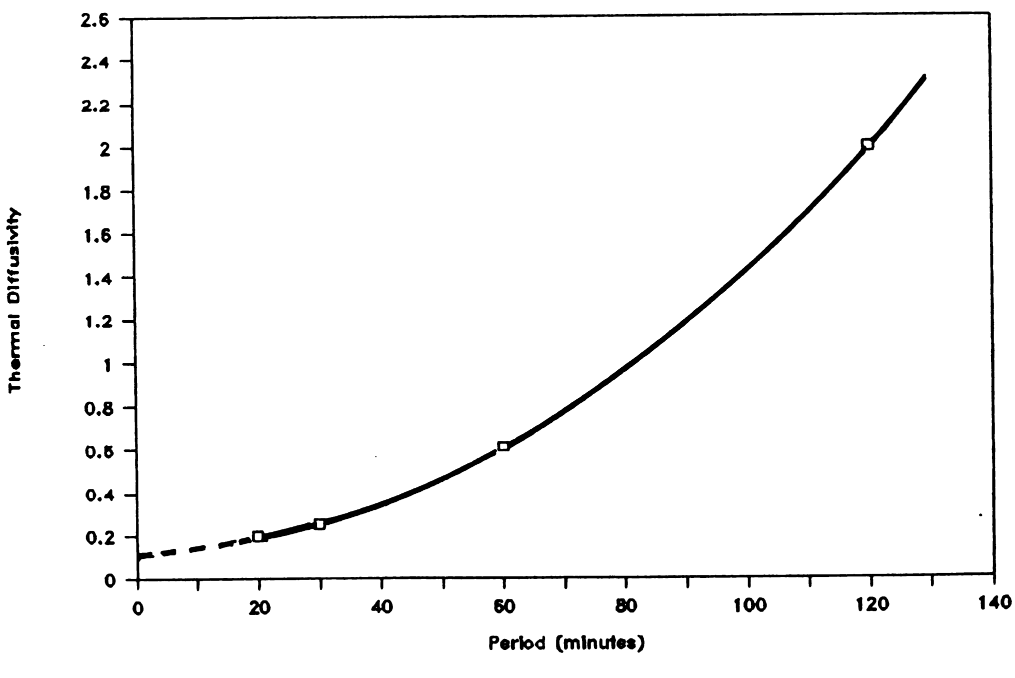

FIGURE 23: Curve extrapolated from the values shown in Table 4 for pine flake mulch (moisture content 9% v/v). Thermal Diffusivity units are x10^{-2} cm^2/sec.

The value of thermal diffusivity for the pine flake mulch obtained from Figure 23 is 0.11 $x10^{-2}$ cm^2/sec. This is consistent with expectations and is comparable to the values shown for Peat in Figure 14.

The basic aim of this method is to obtain values for apparent thermal diffusivity at decreasing thermal gradients (dT/dt). It was therefore concluded that equivalent results could be obtained from a single set of readings for each mulch. This would be possible if the boundary temperature modulation was of sufficient period and amplitude to obtain readable variations through the soil profile. The main advantage of this approach would be the time saved by taking only one set of readings. This saving would be quite considerable as the period required for equilibration between each set of readings was several hours. Also, any errors due to evaporational losses over the duration of the experiment would be minimized.

This method was tested using the same heat cycle technique as used above, with an imposed period of modulation of P=120 hours. An indication of the thermal gradient for each successive depth was obtained at an interval of P/4 (30mins.) after each maximum or minimum. This was achieved by measuring the temperature differential from 10 minutes before (P/12) to 10 minutes after the point in question. The average gradient was then obtained by division of $[T_2-T_1]$ by $[t_2-t_1]$. The graphs of readings and plots made are shown in Figures 24 to 29.

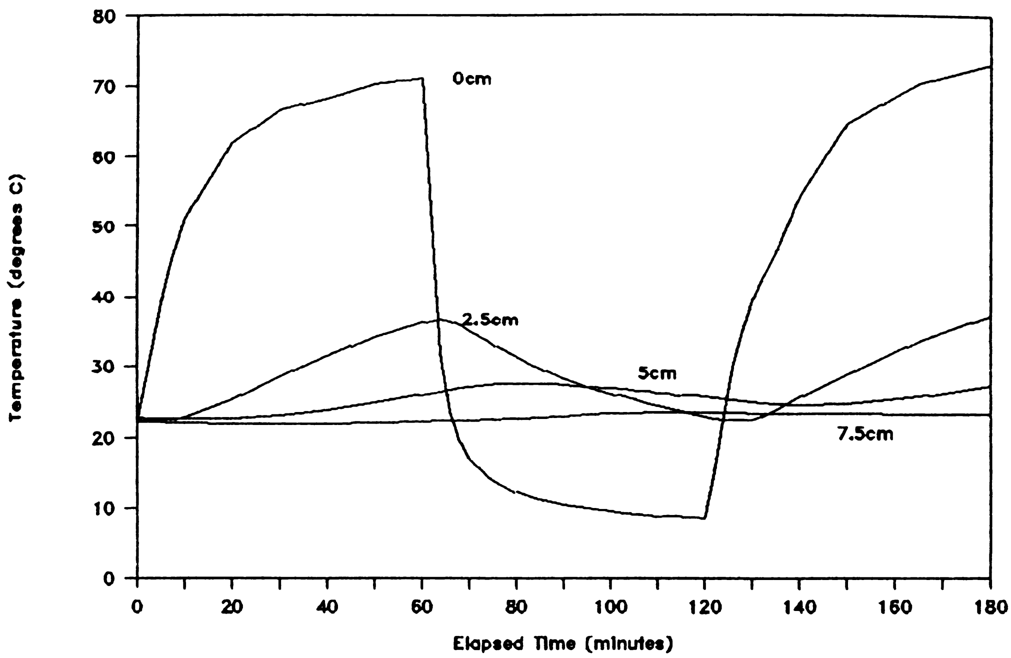

FIGURE 24: Readings taken for wood chip mulch with an imposed period of 120 minutes. (Moisture content 16% v/v)

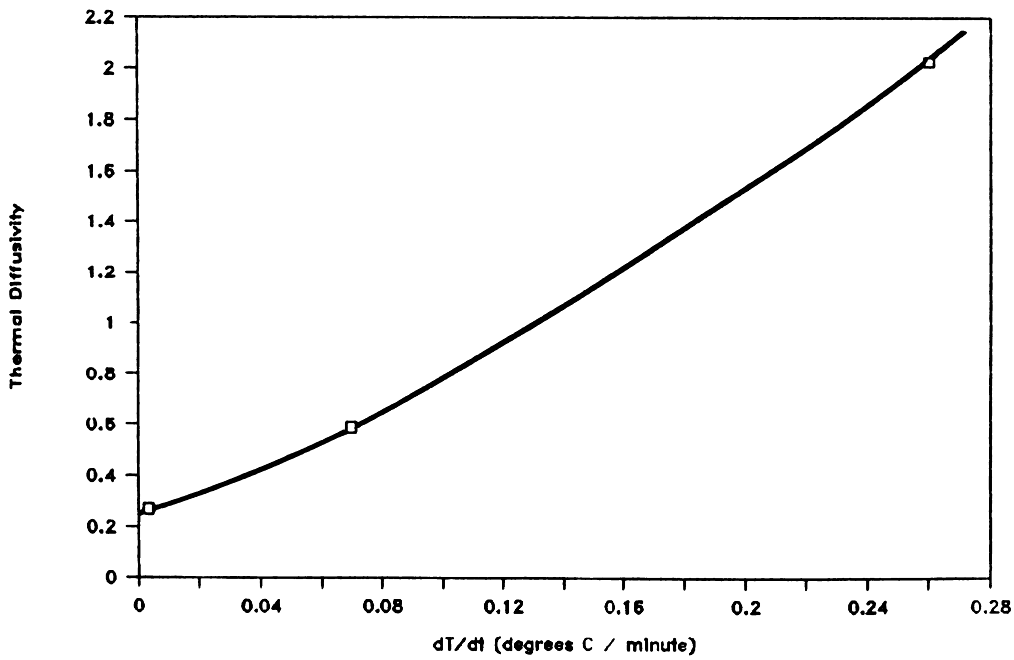

FIGURE 25: Curve extrapolated for wood chip mulch. Thermal Diffusivity units are $x10^{-2}$ cm^2/sec.

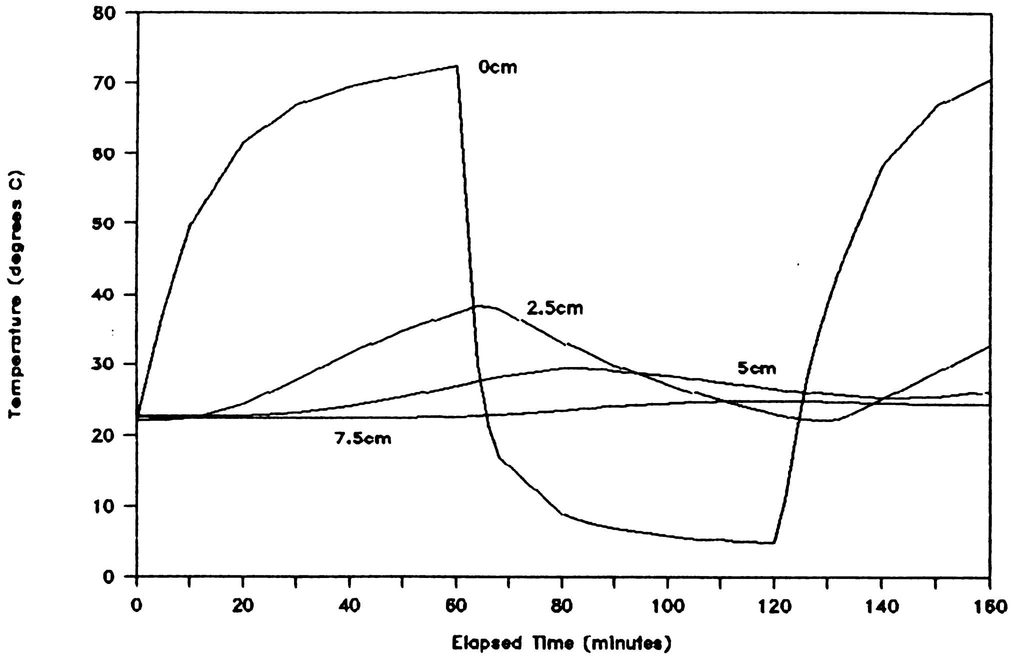

FIGURE 26: Readings taken for pine flake mulch with an imposed period of 120 minutes. (Moisture content 9% v/v)

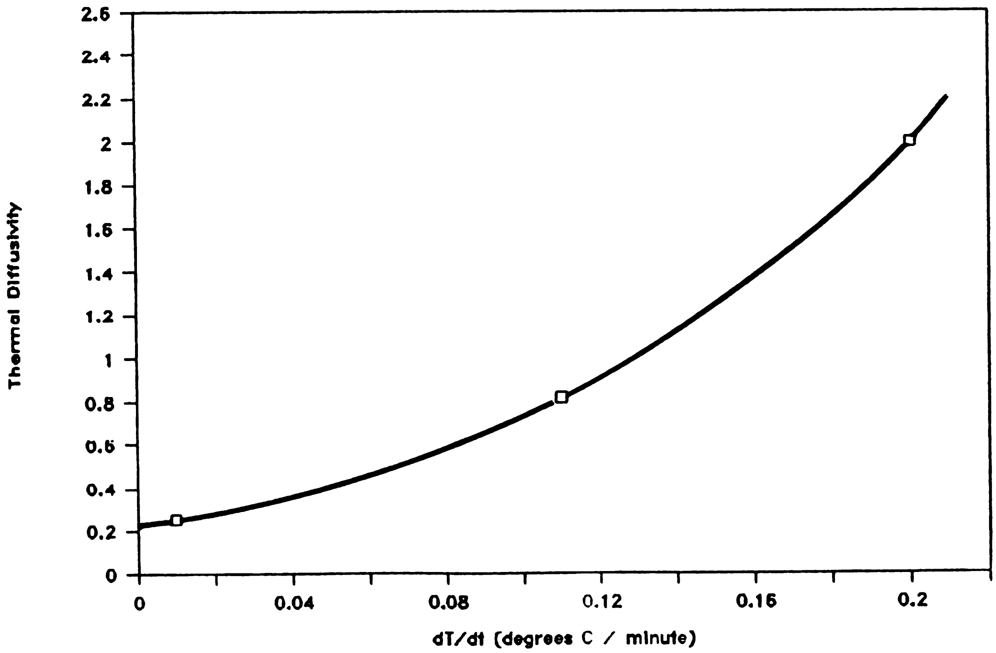

FIGURE 27: Curve extrapolated for pine flake mulch. Thermal Diffusivity units are x10^{-2} cm^2/sec.

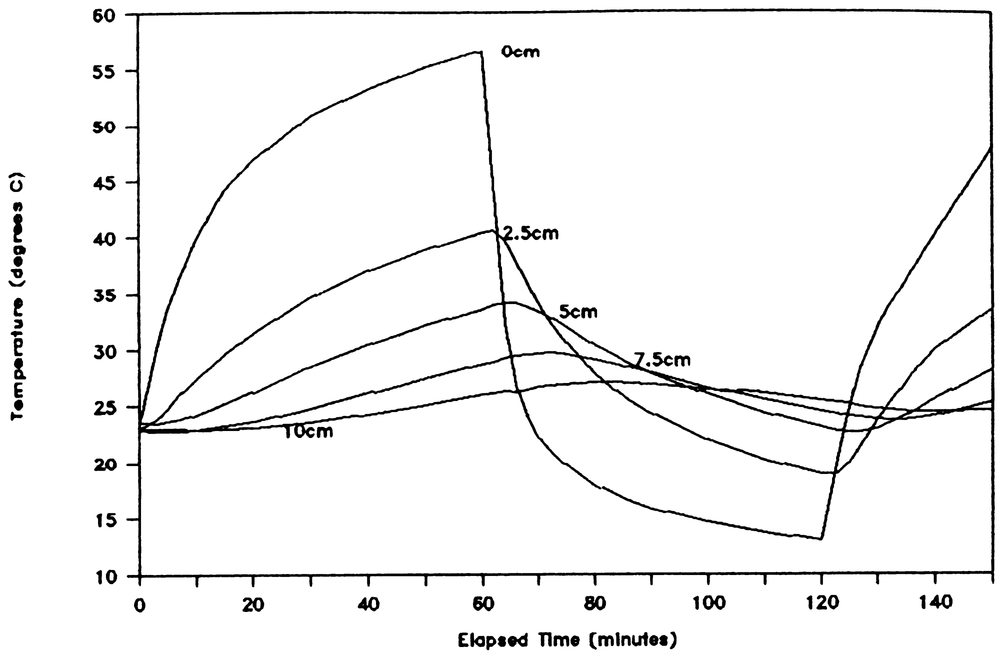

FIGURE 28: Readings taken for river gravel mulch with an imposed period of 120 minutes. (Moisture content 6% v/v)

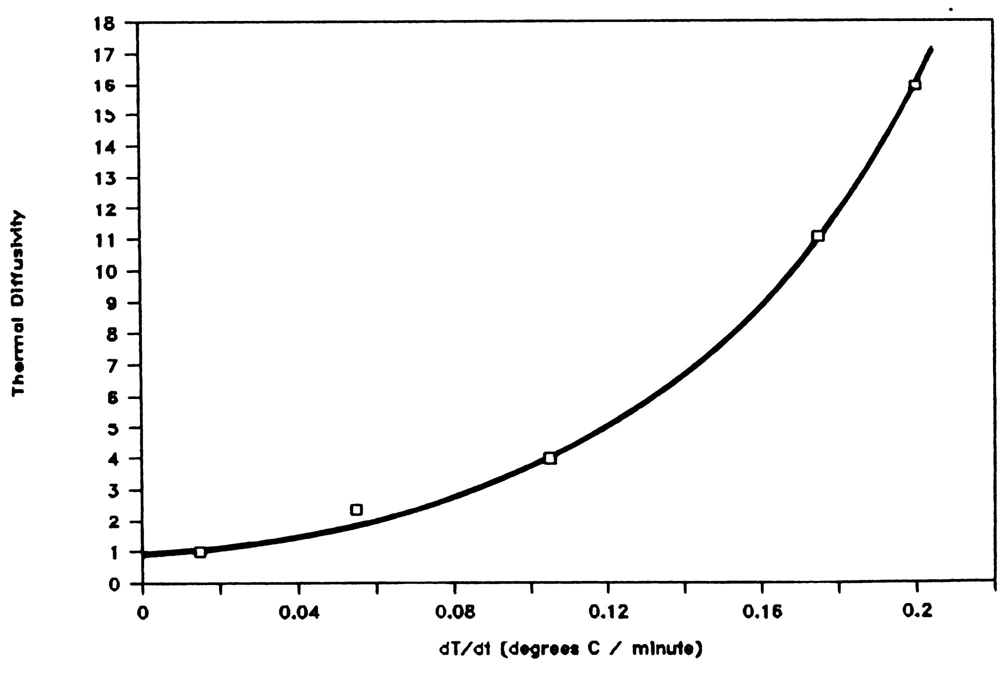

FIGURE 29: Curve extrapolated for river gravel mulch. Thermal Diffusivity units are x10^{-2} cm^2/sec.

The extrapolated values (obtained from Figures 25, 27 and 29) for thermal diffusivity for the three mulches are: $0.25 \times 10^{-2} cm^2/sec$(wood chip); $0.22 \times 10^{-2} cm^2/sec$(pine flake); and $0.8 \times 10^{-2} cm^2/sec$(river gravel). These results clearly indicate that wood chip and pine flake provide much greater insulation than river gravel, and are therefore more suitable for use as mulch, at least within the context of this work.

The above values are within the expected ranges for the respective materials and therefore lend some credibility to this method of analysis. However, the variation between this value for pine flake, which is based on the same results as shown in Figure 21, and the value obtained by Jackson and Kirkham's technique ($0.11 \times 10^{-2} cm^2/sec$) is significant. This variation may be due to drying of the pine flake during the first trials, which would tend to yield a progressively lower value for α. This is quite possible, as the readings for the decreasing period technique took place over several days, and the last cycle was usually heating. This would lead to some moisture loss as the container used was not sealed.

Certainly, in ease and speed of usage, the thermal gradient technique presents a convenient method for assessing the thermal diffusivities of loose mulch materials. The results obtained are certainly satisfactory for comparative purposes with other results obtained using the same equipment. However, these results need to be further verified before reliable comparison with results from different techniques is possible. Improvement of the experimental equipment could be obtained by sealing the mulch container to eliminate moisture losses.

THE THERMAL PERFORMANCE OF A LOOSE ORGANIC MULCH OVER A 12-MONTH PERIOD

Two plots of $9m^2$ were prepared in an open area on sandy loam. One was left as bare ground for a control, and the other was covered with 75mm of loose organic mulch (wood chip). Air, surface and subsoil temperatures were recorded every half hour for a period of 12 months from 22nd April 1985 to 22nd April 1986.

The aim of this experiment was to assess the thermal performance of an unreplenished, loose organic mulch (wood chip) compared to a bare earth control. The trial was run over a 12-month[27] period in order to observe any reduction in mulch efficiency as it decomposed.

As this experiment was conducted in the open, environmental influences were uncontrolled. In order to ensure reliable results, these influences had to be consistent for both plots. This was achieved by constructing the plots in an east-west orientation (in order to ensure equal incident light to both plots) and by locating the plots adjacent to a permeable windbreak (*Coprosma repens*) against the prevailing southerly winds to reduce errors caused by wind turbulence and eddy currents.

The mulch used for this trial comprised chipped leafy branches from *Ficus hillii* and *Lophostemon confertus* (*syn. Tristania conferta*). Approximately 50% of its

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[27] 12 months was selected as a critical period in the initial establishment of seedlings or plants.

initial bulk consisted of foliage and the balance was small branches and wood chip. This mixture was selected as being fairly representative of loose organic mulches as a whole, since it provided an even proportion of rapidly decaying material (leaf) and more durable woody tissue.

The experiment was conducted on a property at Malabar, a southern coastal suburb of Sydney. The site was of uniform elevation in a North-South section and had an East-West slope of 1:30 falling to the West.

The soil was indigenous to the site (a coastal heathland). It was a fairly coarse textured loamy sand with a pH of 6.20 ±0.05 (1:1 H_2O). It contained a low to moderate proportion of fine, ligneous organic particles, with traces of clay. The bulk density at 5% moisture content was 1.37 g/cm^3 with 40% pore spaces. The soil was fairly homogenous to a depth of 0.75 m. Below this level was a thin horizon (25-50 mm) of leached clay and silt particles overlying a bedrock of Hawkesbury sandstone.

The plots were prepared on 20th July 1984 on adjacent strips of earth, each of dimension 1.5 by 6 m. Temperature-sensing probes were inserted horizontally into the soil from a central trench of 150 mm width and 200 mm depth. This trench was then backfilled and tamped prior to mulching. The surface probe was seated horizontally into the soil surface and covered with 2 mm of site soil.

Mulch was originally applied to a mean depth of 75 mm on 20th July 1984. (See Figure 30.) The foliage content of the mulch had undergone significant decomposition by the commencement of trials on 22nd April 1985, and the depth of mulch had reduced to a maximum of 75 mm. Foliage content was almost entirely absent by the conclusion of the trials on 22nd April 1986. (See Figure 31.) Maximum mulch depth at the conclusion of the trials was only 50 mm, with bare earth showing in some areas.

Temperatures were monitored via six probes. The allocation of each probe, together with the mnemonic used in reference to it, is shown in Table 5.

TABLE 5

Allocation of Probes and Mnemonics Used for the Experiment

PROBE NO.	MNEMONIC	LOCATION
1	AIR	Ambient temperature measured from probe located on a nearby wall (see Figure 33)
2	G200	200mm beneath bare ground
3	G125	125mm beneath bare ground
4	G0	At bare ground surface
5	M200	200mm below 75mm of mulch
6	M125	125mm below 75mm of mulch

FIGURE 30: View from above showing the mulch and control plots on 20/7/84. Note initial leaf content of the mulch.

FIGURE 31: View from above of mulch plot at completion of the experiment. Note lack of leaves. (22/4/86)

FIGURE 32: Probe #1, used for monitoring ambient temperatures, mounted in a protective housing.

FIGURE 33: The temperature monitoring and recording apparatus used for the duration of the experiment.

The probes used were semiconductor temperature sensors housed in 150mm lengths of 5mm diameter brass tubing. This, in conjunction with the horizontal placement of the probes, provided an isothermal region around the sensor, thereby providing a more accurate mean temperature reading for each level. Signals from the probes were run in shielded wires to the monitoring and recording equipment located in a nearby house. (See Figure 33.) This equipment consisted of a signal processing unit, a microcomputer and a dot-matrix printer. Signals were processed and stored in memory as degrees Celsius. Results were printed each day following the 9 a.m. readings. These printouts showed temperatures for each probe and mean daily temperatures together with variance and standard deviation.

The time of each set of readings was accurate to within ±3 minutes of Eastern Standard Time (E.S.T.) for the duration of the experiment. Probes were individually calibrated in stirred water baths to an accuracy of ±0.1°C. However, maximum resolution of the monitoring apparatus was 0.5°C. Accuracy was therefore never worse than ±0.5°C for the duration of the experiment. Weeds in the control and mulch plots were treated every two weeks with contact, non-residual herbicide in order to minimize soil surface disturbance.

Temperatures for each probe were sampled and processed at half-hourly intervals on the half-hour and hour

(E.S.T.). Day numbering was based on sequential numbering of the calendar year. By this system, the experiment was commenced on Day 112, 1985, and completed on Day 112, 1986.

Rainfall records were obtained from the 9 a.m. Daily Rainfall Registrations for the Sydney Metropolitan Area, supplied by the Bureau of Meteorology. Total incident rainfall from the 22nd April 1985 to 22nd April 1986 was 1,286.8mm. (See Figure 34.)

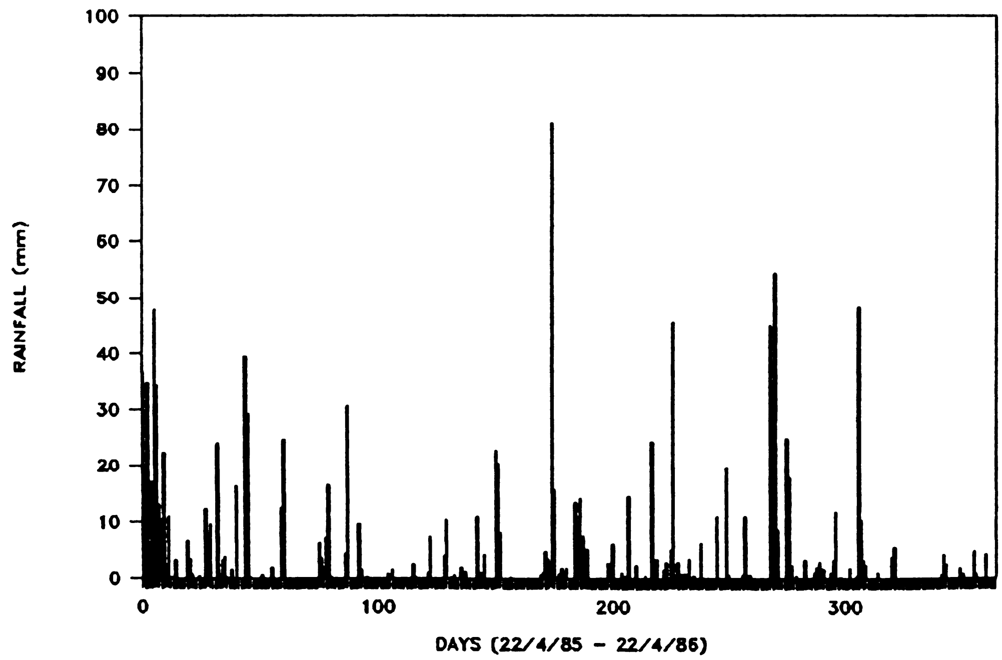

FIGURE 34: 9 a.m. daily rainfall registration for the duration of the trials. Data courtesy of the Sydney Bureau of Meteorology.

Results

Performance of the mulched plot versus the control (bare-earth) plot was assessed on the basis of 9 a.m. temperatures and mean daily temperatures (with standard deviations). These figures were transcribed from the daily printouts into log books. These data were then entered into a computer for further analysis and display. The mean values for both sets of temperatures over the duration of the experiment are shown in Table 6. Graphs for the 9 a.m. temperatures for each probe are shown in Figures 35 to 40. Graphs for mean daily temperatures are not shown due to the high level of correlation between the two sets of readings.

Soil temperatures at both depths under the wood chip were substantially more stable than those 200mm beneath the bare earth. (See Table 6.) The standard deviation for daily mean temperatures for both probes under mulch was only 0.3. In fact, it was not uncommon to find only 0.5°C variation in temperature over 24 hours for both probes.

TABLE 6

Maximum, Minimum and Mean Values for the Two Sets of Readings over the Duration of the Experiment (22/4/85 to 22/4/86)

All temperatures in °C	#1 AIR	#2 G200	#3 G125	#4 G0	#5 M125	#6 M200
9 A.M. TEMPERATURES:						
MAXIMUM:	29.5	25.5	26.5	39.0	24.0	23.5
MINIMUM:	7.0	8.0	5.0	4.0	8.5	9.0
RANGE:	22.5	17.5	21.5	35.0	15.5	14.5
MEAN:	18.3	17.2	16.2	19.4	17.0	16.7
STANDARD DEVIATION:	5.2	4.8	5.5	8.5	4.6	4.6
MEAN DAILY TEMPERATURES:						
MAXIMUM:	27.2	27.5	29.0	32.4	24.2	23.7
MINIMUM:	8.8	8.6	6.6	5.7	8.9	9.0
RANGE:	18.4	18.9	22.4	26.7	15.3	14.7
MEAN:	17.9	18.6	18.4	19.3	17.4	16.9
STANDARD DEVIATION:	4.5	5.4	6.1	6.8	4.7	4.6
MEAN DAILY STANDARD DEVIATION:	2.3	1.1	2.5	6.0	0.3	0.3

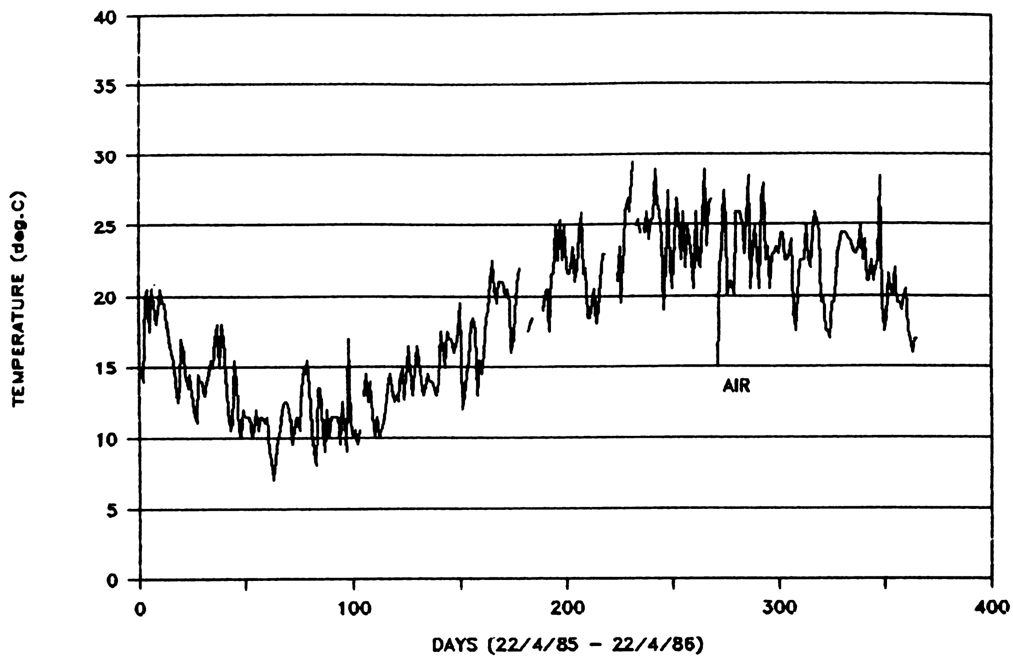

FIGURE 35: Probe #1: 9 a.m. ambient temperatures. Discontinuity is due to power supply problems during the tests.

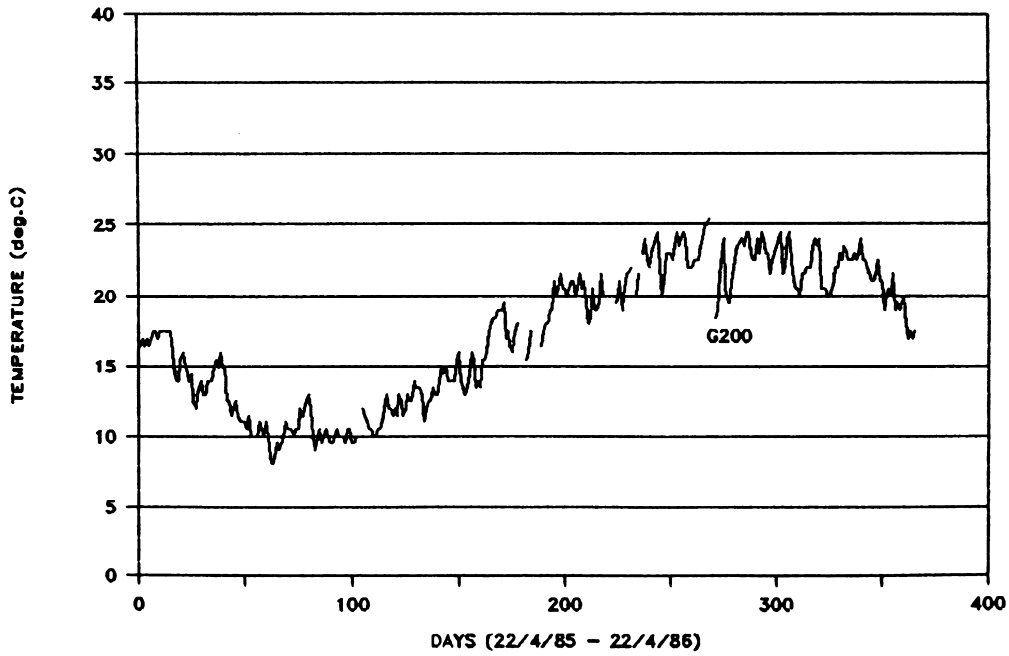

FIGURE 36: Probe #2: 9 a.m. temperatures 200mm below bare ground (control). Discontinuity is due to power supply problems during the tests.

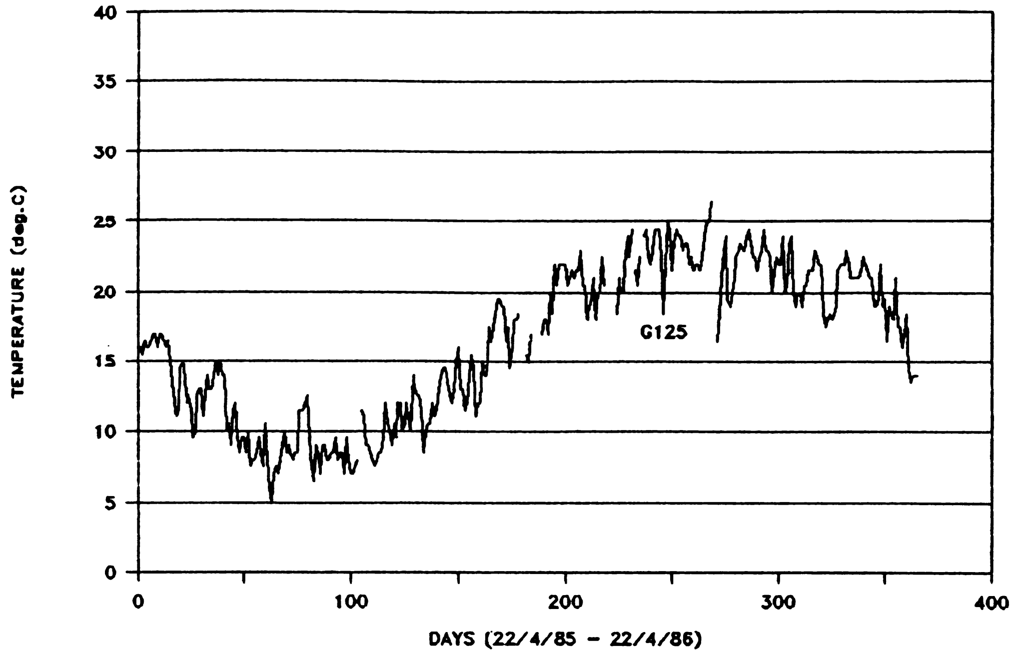

FIGURE 37: Probe #3: 9 a.m. temperatures 125mm below bare ground (control). Discontinuity is due to power supply problems during the tests.

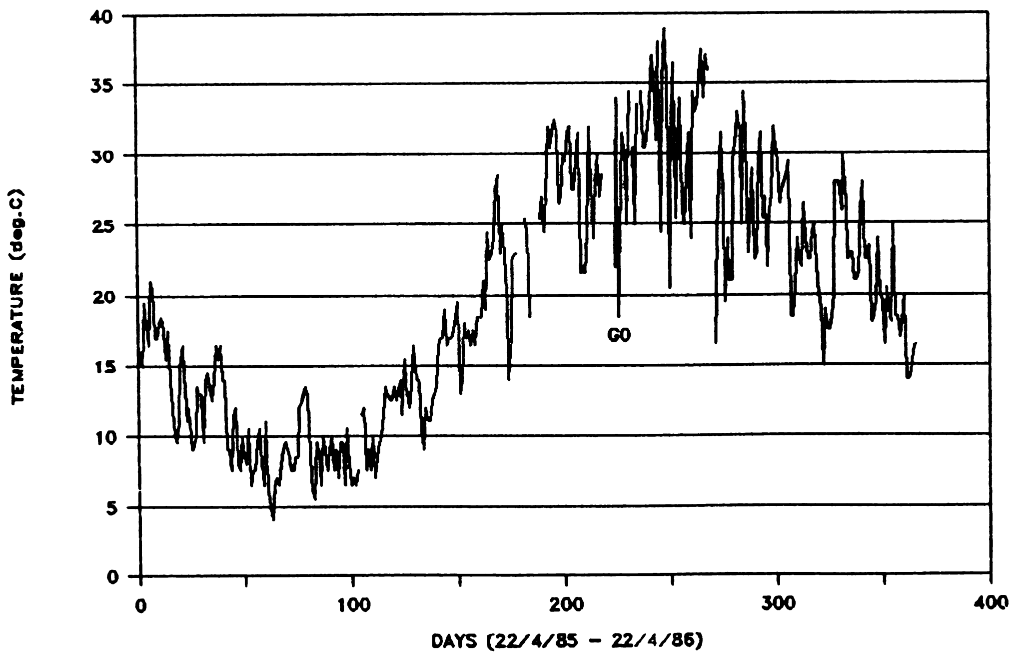

FIGURE 38: Probe #4: 9 a.m. temperatures at the bare ground surface (control). Discontinuity is due to power supply problems during the tests.

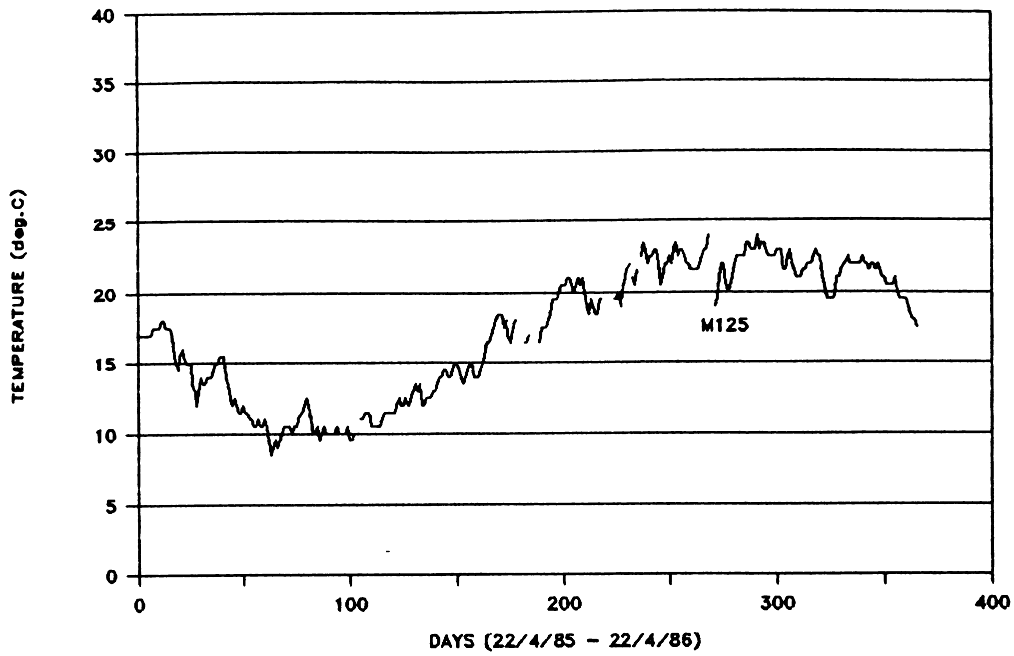

FIGURE 39: Probe #5: 9 a.m. temperatures 125mm below 75mm of loose organic mulch. Discontinuity is due to power supply problems during the tests.

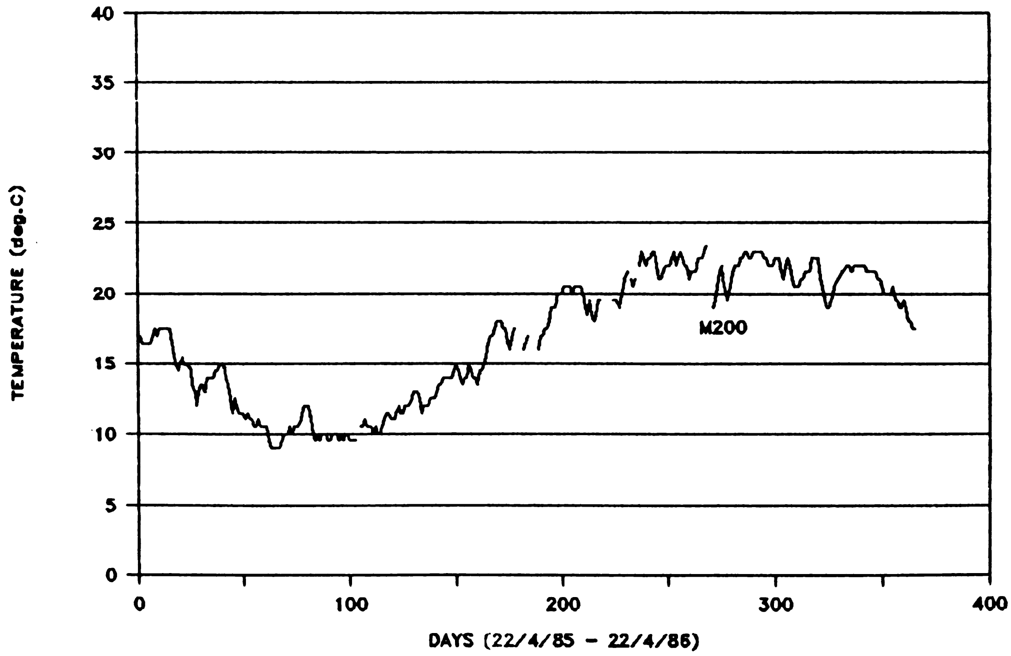

FIGURE 40: Probe #6: 9 a.m. temperatures 200mm below 75mm of loose organic mulch. Discontinuity is due to power supply problems during the tests.

Variation in the performance of the mulch over the 12 months of observation was assessed by variation in the apparent thermal diffusivity of the mulched plot versus the control. Thermal diffusivities were calculated on the basis of time lags for the diurnal cycle (Period (P) = 24 hours = 8.64×10^4 sec). This was done using the time lag relation (Equation 2.4):

$$\alpha = P/4\pi \cdot (\delta x)^2/(\delta t)^2$$

where α = thermal diffusivity,

P = period of the alternating temperature applied,

δt = lag time over distance δx.

Only the time lags measured for the depth of δx = 200mm were used, as the longer times involved improved the accuracy of the calculations. The thermal diffusivity was computed directly from the time lag after substituting values for P and δx,

i.e.

$$\alpha = 8.64\text{x}10^4/4\pi \cdot (20)^2/(\delta t)^2$$

$$= 2.75\text{x}10^6/(\delta t)^2$$

Time lags were measured on the basis of daily maxima over approximate 10-day intervals over the duration of the experiment. The actual intervals varied as only days with clear surface maximum temperatures were used. Also, no reliable measurements could be made for the whole month of June 1985 as temperatures beneath the mulch did not vary sufficiently to provide reliable readings.

Calculated thermal diffusivities for the two sets of 200mm readings are shown in Figure 41.

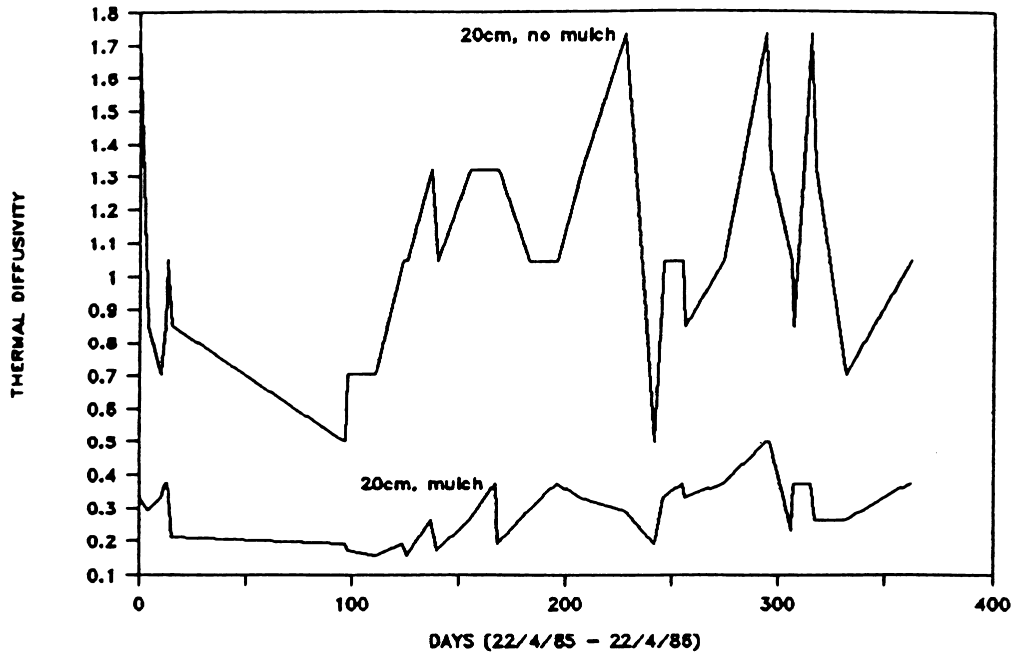

FIGURE 41: Variations in thermal diffusivities for mulched versus unmulched plot over the duration of the experiment. Thermal Diffusivity units are $x10^{-2}cm^2/sec$.

From Figure 41, the range of thermal diffusivities obtained for 200mm beneath 75mm of wood chip is 0.17 to $0.5x10^{-2}cm^2/sec$. This compares very favourably with the value of $0.25x10^{-2}cm^2/sec$ obtained for pure wood chip (at 16%H_2O v/v) in the previous experiment. It should also be noted that the diffusivities plotted above represent values for the full range of moisture content from air dry to saturated. The correspondence between moisture content and thermal diffusivity is easily observed by comparing the daily rainfall shown in Figure 34 with the values plotted above. Peak diffusivities coincide with periods of heavy rain, and troughs occur after periods of no rain.

Some conclusions of practical significance can be drawn from these results. Firstly, a relatively thin layer of wood chip (75mm) is sufficient to create conditions 200mm beneath the ground that correspond to results obtained for pure wood chip. Secondly, the thermal performance of a wood chip mulch is relatively stable (compared to bare earth) over a wide range of moisture contents.

It was expected that the thermal performance differential between the mulched plot and the control would decrease over the 12 months as the mulch decomposed. However, as can be seen from Figure 41, despite considerable deterioration in the depth and content of the mulch during the experiment, there was no significant decline in its performance over the 12 months of observation. This was attributed to its effect on the soil surface condition. When the mulch was removed at the completion of the experiment, the underlying top soil was found to have:

(i) open, friable texture;

(ii) high organic matter content, compared with the trace content in the control;

(iii) improved aeration and structure compared to the control;

(iv) a large earthworm population, in excess of 10 per $300mm^2$, compared to the negligible ($<1/300mm^2$) population in the adjacent bare-earth control plot. This was attributed to the higher organic matter content, lower maximum temperatures and higher moisture levels obtained in the mulched plot compared to the control[28].

Aside from the simple temperature-related effects, these changes to the soil would offer many advantages to establishing vegetation by providing increased infiltration rates, increased soil water and nutrient holding capacities, and increased aeration.

In practice, organic mulches are applied in conjunction with plants. This further enhances the above effects, since, as the mulch deteriorates, the plant growth compensates for any loss in performance by the mulch.

These results clearly indicate that the use of loose organic mulches, such as wood chip, provide a simple, and highly effective, means of assisting plant establishment. This is achieved by amelioration of climatic extremes and enhancement of the soil environment.

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[28]Temperatures below 25°C, high levels of organic matter and high levels of available soil moisture are essential requirements for earthworm survival and growth (Handreck and Black, 1984, pp. 289-290).

CONCLUSION

This work clearly identifies the importance of adequate site inspection and analysis during the design stage of landscape projects. It is at this stage that potential dry areas can be noted, and some assessment made of their predominant causes. The functional separation of these causes into climatic factors, soil-related factors, and weed competition (as was shown in Figure 2) enables preliminary selection of suitable techniques. These techniques can then be incorporated into site-specific solutions, such as the typical details shown in Figures 4 to 12.

However, as was stressed in the introduction, these techniques are applied for plant protection and support during the establishment phase. As such, they are effective tools only when the selected plants are capable of growth in the given conditions. The selection of plant species is of fundamental importance in determining whether soil moisture levels are adequate or limiting for plant growth. This is apparent by the definition of dry areas as any areas where lack of available soil water presents a major threat to the survival and growth of the selected plant species.

Of the techniques covered, irrigation offers the most direct, and potentially the most effective, approach to the problem of low levels of soil water by simply supplementing the supply of water to the plant. The diverse range of irrigation methods and control mechanisms covered enables the design of appropriate systems for any application where suitable water is available. However, the importance of thorough site inspection prior to designing a system of irrigation cannot be overstressed. Selection of systems that are unsuitable for the site conditions can result in water wastage, disproportionate plant growth, salinity problems, runoff and erosion. Often irrigation is best employed in conjunction with other techniques that increase infiltration rates, reduce runoff and improve soil water holding capacity.

Windbreaks and shelterbelts have been found to significantly ameliorate the adverse effects of wind on the microclimate. The use of medium-porosity windbreaks can reduce evapotranspirational losses and improve plant water-usage efficiency in affected areas.

Weed control has been found to be extremely effective in reducing unnecessary soil moisture depletion, and in improving the appearance of the site. These benefits are sufficiently great to justify the routine specification of some form of weed control on all landscape projects. This can be achieved quite efficiently by using a combination of the techniques covered. For example, a single application of knockdown herbicide, followed by cultivation and mulching. This method can achieve effective and quite long-lasting results while providing only minimal disruption to the environment.

Site preparation and planting techniques can provide the possibility of quite elegant design solutions. Through careful planning, elements such as planters, mounds and furrows, can be used to satisfy the brief requirements as well as to ameliorate potential dry areas on the site.

Mulches, aside from their visual qualities and weed suppression, offer numerous other benefits for assisting plant establishment. Indications from the preliminary results obtained are that even a fairly thin (5cm) layer of loose organic mulch can offer substantial reduction in soil temperature ranges. This should also entail good evaporation suppression. The consistent performance of wood chip mulch as it decomposed over a twelve month period, together with the observed soil improvements, provide further evidence of the beneficial effects of loose organic mulches on the soil environment.

The work on mulches has only touched the surface of a whole new field of study. If carried further, this research is potentially of great benefit to Landscape Architecture, as well as Horticulture and Agriculture. It really is surprising that so little work has been done to date in this area. From the work done in this thesis, it is apparent that the thermal diffusivity of loose mulches will prove a reliable indicator of their thermal performance. The hypothesis proposed, that this in turn will provide good indication of their efficiency in evaporation reduction, obviously needs to be tested.

The experimental apparatus and method developed appear suitable as a starting point for this research. With the minor modifications suggested, this method can be used to obtain comparative thermal diffusivity values for the whole range of loose mulches in use. It is then a relatively simple matter to run replicated evaporation trials to establish the degree of correlation between the the thermal diffusivity of the mulch and the observed evaporation reduction.

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