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THE EFFECT OF TREES ON SOIL STABILITY OF HILL COUNTRY SOILS: A STUDY OF TRANSPIRATION AND ROOT DISTRIBUTION

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Title: **THE EFFECT ON SOIL STABILITY OF HILL COUNTRY SOILS: A STUDY OF TRANSPIRATION AND ROOT DISTRIBUTION**

Executive Summary:

Transpiration of single trees can be measured in a hill-country field situation using a dedicated logging system, and weather can be measured concurrently using a system based on the Campbell 21X recorder.

Canopy conductance can be calculated for single trees using such transpiration and micrometeorological measurements, to extrapolate to similar trees in similar situations, and to characterise the response of the tree to changes in environment, notably declining soil water content.

Calculated values of the decoupling coefficient indicate the radiative component of transpiration is larger than the advective component; the range is 0.15 to 0.25.

The root-coring technique can be used in the hill-country situation to characterise root distribution, even though soil variability can be substantial.

In general depth of rooting is limited to substantially less than 1 m, and the root development and size-class distribution is affected by the frequency and degree of flooding, whereby large root development is inhibited by dieback.

The study indicates a satisfactory framework to establish the effect of soil limitations on re growth (including species interactions), and the effect of trees on soil strength. In particular it is possible to decide on the relative contributions of root strength, and of lowering soil water content on soil strength.

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1.0 Abstract

Transpiration from three Populus trees was measured for several months using the heat-pulse method, and concurrent measurements of micrometeorological variables were made.

Root-length density and size distribution were estimated for the same trees using a root coring technique.

The results show that the methods allow good characterisation of water use and root systems, enabling future work to relate soil conditions to growth, and to investigate two mechanisms whereby trees might enhance soil stability, vis. by root reinforcement, and by enhancement of soil strength through removal of soil water.

2.0 Introduction

Planting of trees for soil conservation purposes is a well-established practice both in New Zealand and overseas, and the gains in soil stability have been demonstrated in limited surveys. The basic mechanisms which have been proposed for such increases are so diverse and there are so many apparent contradictions that basic studies are warranted, so that conservation practices can be focused more closely. For instance, de-watering by transpiration from deciduous trees is thought to increase soil stability by lowering soil water content, but soil water content appears to be rapidly made up during the early winter rains when the trees are bare. Again, tree roots tend not to cross potential or actual slip planes but are associated with increased soil stability; also the presence of trees adds weight and there is a lever action in winds, but there is not an association between presence of trees and increased slops.

Thus there is a need to identify the mechanisms whereby the presence of trees increases soil stability.

Two primary approaches were taken: (i) to quantify the amount of water transpired by single spaced trees, and (ii) to measure the root distribution of the same trees so as to establish the likely zone of influence of the root system.

3.0 PART I: Transpiration

3.1 Preamble

Transpiration is the net result of evaporative demand from the atmosphere, ability of the soil and root system to supply, and the nature of plant resistances (and perhaps tissue storage) mediated particularly by canopy resistance - the sum of all the stomata resistances. Canopy resistance therefore, is the site where the tree can control water loss, preventing excessive loss in times of drought yet taking full advantage of ability to transpire and simultaneously absorb carbon dioxide for photosynthesis when water is available. Estimation of this parame ter will not only indicate the extent of transpiration which is potentially possible in any given micrometeorological conditions, but also indicate when water is becoming limiting.

Measurement of water loss from large trees is more difficult than from smaller plants only because of scale. There are three broad approaches: (i) by measuring uptake from the source, i.e. the change in soil water, (ii) by measuring the flux from the foliage, or (iii) by measuring flow past a point within the plant - obviously the trunk is a logical site, and the one we chose for this study.

We used the heat-pulse method, where a pulse of heat is used as a marker carried by the transpiration stream past sensors. Using the physics of flow within a porous medium, derived measurements of sap velocity can be aggregated to give fluxes, which can in turn be aggregated over time to give say, daily or weekly water use.

Such measurements are of little use unless they can be related both to the size of the tree, the zone of influence of the tree, and the evaporative demand from the atmosphere. Therefore we made measurements of the tree. of the micrometeorology and of the root zone (see section

5.0 for the last-named). We derived estimates of canopy resistance for the limited time we were able to take measurements, and also the decoupling coefficient (omega). The latter indicates how well the foliage is coupled to the atmosphere (and thus the proportion of transpiration which is driven by radiation and that driven by "advection" -energy carried to the foliage by air flow).

3.2 Methods

3.2.1 Measurement of Transpiration

All water transported from soil to leaves moves through the sapwood xylem as continuous columns of water, according to the cohesion-tension theory of sap flow. Therefore the trunk of a tree with it's clearly-identifiable sapwood is a convenient site to measure transpiration rate.

Functional sapwood comprises three physical phases: a matrix of woody tissue, liquid as cellular contents, interstitial water and the transpiration stream, and gas in both interstitial spaces and the lumens of cells. In the case of gymnosperms, sapwood primarily comprises a complex of tracheids interconnected by pit pairs, and in hardwoods, a matrix of vessels often of considerable length within parenchyma tissue. Other structures such as resin canals, radial rays and cambium are materially similar to parenchyma, or volumetrically small.

Where xylem tissue is diffuse-porous and homogenous over a scale of millimeters, we can consider the sapwood to be physically similar and amenable to analysis of transport characteristics such as heat and mass transfer. Heat introduced into the xylem tissue as a marker will be transported by both conduction, and by convection as the transpiration stream moves through the tissue. A simple system of point source and single downstream sensor will confound these two transfer mechanisms, and render the centre of the moving heat pulse difficult to identify. Further, interchange of heat between the moving sapstream and the matrix means that the heat pulse will appear to move more slowly than the sap within the lumens of the conducting tissue. A corollary is the movement of dye behind the solvent front in chromatography. Finally, insertion of heaters and temperature probes into the sapwood will violate an assumption of physical homogeneity.

Three technical advances each separated by more than 20 years have enabled sufficient understanding of the physics of flow to permit absolute field measurement of sap velocities.

(i) Huber (1928) originally devised a simple heater wire and thermocouple system to indicate relative sap velocities from sensing of heat pulses. He was also involved in the development of the so-called 'compensation' system (Huber and Schmidt (1937) which comprised a thermocouple pair implanted upstream and downstream from the heat source. A larger distance to the downstream sensor allowed separation of the conductive and convective elements of the movement of a pulse of heat. Since the heat pulse reaches the closer upstream sensor first (heat movement by conduction is substantially faster than by sapstream mass transport), an output from the thermocouple pair is obtained which returns through zero as the heat pulse is carried through a point equidistant from each sensor. The time taken from initiation of the heat pulse until return through the zero output, combined with the distance from the heat source to a point midway between the sensors allows calculation of the heat pulse velocity.

This elegant device allowed separation of the transport mechanisms of conduction and mass flow.

(ii) Marshall (1958) pointed out that heat pulse velocity could not be equated with sap velocity because interchange of heat meant that the heat pulse moved as if sap and matrix was a single medium. Consequently the ratio of heat pulse velocity (Vh) to sap velocity (Vs) within the conducting lumens was a function of three other ratios: (i) cross-sectional area of the lumens (a) to total sapwood area (A), (ii) density of sap (sigma-s to density of sap plus matrix (sigma-sm), and (iii) heat capacity of sap (Cs) to that of sap plus matrix (Csm). Therefore expressing sap velocity on the basis of total sapwood area (V'-s) we have:

Y-s = V-s . a = A . V-h . Cs . sigma-s / (Csm . sigma-sm) (Eq. 1)

The matrix material of woody plants is largely composed of hemi-celluloses and has remarkably similar properties even between morphologically dissimilar species. Of particular interest is the specific gravity, taken as 1530 kg/m^3, and specific heat, taken as 1.38 x 10^6 kJ/kg/^{o} Celsius. Expressing the three phases of matrix, liquid and gas as volume fractions Vm, V1 and Vg respectively, we have

sigma-sm = 1530 Vm + 1000 V1 kg/m"3 (Eq. 2)

and

Csm = 1.53 . Fm . Cm + Cs . Fl / (F1 + 1.53 . Fm(kJ/kg per oC) (Eq. 3)

Substituting into equation 1 we have:

ie V'-s = Vs (0.505 Vm + A) (Eq. 4)

(iii) Even after implementation of Marshall's concepts, serious discrepancies remained between velocities estimated with the heat-pulse method and independent methods such as weight loss of potted plants. Swanson and Whitfield (1981) showed that implantation of even small-diameter probes significantly violated the assumption of sapwood homogeneity. They set up a computer model verified experimentally, which showed how both the material used in the probes, and the lens of **woody matrix which** was rendered non-conductive by the implantation damage, affected isotherms as they developed as a result of a heat pulse. Because the model takes substantial computing power, they reported curve-fitted parameters for standardised probe materials, spacings and wound sizes. This has enabled correction for the effect of wounding if similar probes are used.

Analysis of sap velocity patterns from multiple simultaneous measurements at one height in the stem allow spacial integration for flux estimates. Both radial and circumferential variation must be considered; the former is of more importance except where the tree has pronounced non-uniformity, such as no the edge of a forest or light pool, or at a stream edge. These should be considered as a special case, with appropriate experimental design.

Radial variation however is substantial, and also varies throughout the day apparently because some water within the stem is available for initial transpiration early in the day and is replenished in part during the night. This is evidenced both as a phase change and as changed patterns of water movement at a given level within the stem. Therefore it is necessary to make an individual assessment at each sampling time.

By assuming that velocities in concentric rings are the same, implantation of a number of probes at different depths will provide data suitable for fitting a relationship between velocity and depth below the cambium. A second-degree polynomial is appropriate:

$$V' = ax^2 + bx + c \qquad \text{Eq. 5}$$

where x is the distance below the cambium and a, b, c are fitted parameters.

The solid of revolution found by rotating the curve about the stem axis represents the sap flow, since the vertical axis has dimensions of velocity and the two horizontal axes, area. The limits used are the cambium and the sapwood/heartwood boundary, unless the curve goes negative inside these limits. The product is a flux, since essentially we multiply the sapwood are by the sap velocity.

A dedicated logger has been developed to make measurements at defined time intervals for periods of up to several weeks at a time. Data is down-loaded to a portable PC and the tree dimensions and characteristics added for final production of continuous flux data.

3.2.2 Description of Site and Trees

The site chosen for the initial investigation was on the farm of Mr John Cousins, Zigzag Road, Ashhurst, Palmerston North. It comprised a fan at the bottom of a gulley with the soil formed from material washed from the hill above, comprising a fine sandy loam with no mottles until about 1.4 m depth. Three trees were selected, being 5-year old *Populus deltoides x P. ciliata* planted as 2-year old seedlings. The site was generally sheltered well by the surrounding hills and a pine plantation some 100 m distant up the gully; consequently growth was excellent at some 6-7 m height and 100150 mm dbh.

The three trees were implanted between 20-23 April 1990 with heat pulse probes, and transpiration was logged continuously through leaf-fall until the end of June. Photographic and anecdotal records were maintained of the onset and extent of leaf fall, at each visit (approximately 1-week intervals).

3.2.3 Micrometeorological Measurements

At the same time a weather station was established at a height of 2.5 m at a point midway between the three trees. This measured radiation, ambient temperature, relative humidity and wind speed continuously, with data cumulated to coincide with the data measurement times of the heat-pulse equipment. Radiation was measured with a Li-Cor Pyranometer, temperature with a shielded thermistor, wet-bulb temperature with a similar thermistor fitted with a wick maintained wet by a Mariot bottle system, and wind with several anemometers.

3.2.4 Data Manipulation

In order to normalise the data, leaf area of each tree was estimated from an established relationship between leaf area and sapwood area.

Boundary-layer conductance at the single leaf level was calculated from measurements of the characteristic leaf dimension (assuming the diameter of circular leaves) and wind speed, vis:

ga = 0.0173 . p ^(-.56) . SQRT(u/d) / AI

where ga = boundary layer conductance (m/s) p is the ratio of leaf area to frontal area (a measure of horizontal leaf density) u = wind speed (m/S) d = characteristic leaf dimension (m) AI = leaf area (m2)

Canopy conductance was back-calculated from the Penman-Monteith equation which relates evaporation to micrometeorological variables and vegetation characteristics in a physically realistic way, vis:

gv = L.E Gamma/(cp.Rho.D - s(LE - Rn)/ga)

where
L = latent heat of evaporation of water
E = Flux of water evaporated
Gamma = psychrometric constant
cp = latent heat of air
Rho = density of air
D = vapour pressure deficit
s = slope of saturated vapour pressure/temperature curve
Rn = net radiation
ga = boundary-layer conductance, as before.

Estimating net radiation for the tree required a simple model to describe how radiation was intercepted during the day. The tree under study was described as an ellipsoid, from slide photographs taken of the tree with a 1.5 m scale. The critical measurements are the long and short axes; if the ellipsoid is considered to be truncated, then the depth of canopy from widest point to base is measured. Sun angle is calculated from time of day, day of year and latitude for the time period under consideration. Net radiation is taken as the sum of vertical and horizontal components using projected vertical and horizontal areas respectively, and a simple extinction relationship involving leaf density, assuming an average. While this model is crude, subsequent analysis has shown that it is sufficient since the radiative component is small compared to the advective component of energy used for evaporation from single exposed trees.

The decoupling coefficient, omega (which describes how well the leaves are coupled to the air and therefore the proportion of evaporation associated with radiation compared to the proportion associated with the vapour pressure deficit) was calculated as:

omega = (s + gamma)/(s + gamma. ga . (l/ga + l/gs))

3.3 Results

3.3.1 Transpiration Measurements

Continuous measurements were maintained for all trees except for several difficulties with flat batteries or other events which caused data loss.

These episodes emphasised the desirability of using independent loggers and replicated trees in a hill farm situation, where unattended measurements for extended periods is attempted. We present here indicative data only for the three trees, since the total amount of data collected was large (Figure 1).

Transpiration declined in proportion to leaf area loss with leaf fall, becoming indistinguishable from zero when leaf fall was complete.

Since the micrometeorological measurements made were generally rather well correlated, quite good relationships can be seen between almost any and the corresponding transpiration measurements. All three trees were closely similar in their daily march of transpiration loss, except for occasional nocturnal differences where one tree apparently opened its stomata while the others did not. Generally however nocturnal opening was coincident in all

three trees.

The Penman-Monteith equation provided a better insight into the mechanisms involved in transpiration (Fig 2). Data for two rather dissimilar days is used to back-calculate canopy conductance, boundary layer conductance and the decoupling coefficient. In all such estimates it is necessary to remove from consideration that data which pertains to wet foliage, since different processes are at work. Further, such estimates can only be reliable if substantial transpiration is taking place, since otherwise the errors involved in making small flow estimates dominate the subsequent calculations. Fig 2 demonstrates that (when the total leaf areas of the trees is taken into account) the levels are in accord with values published in the literature (eg McNaughton and Jarvis 1983).

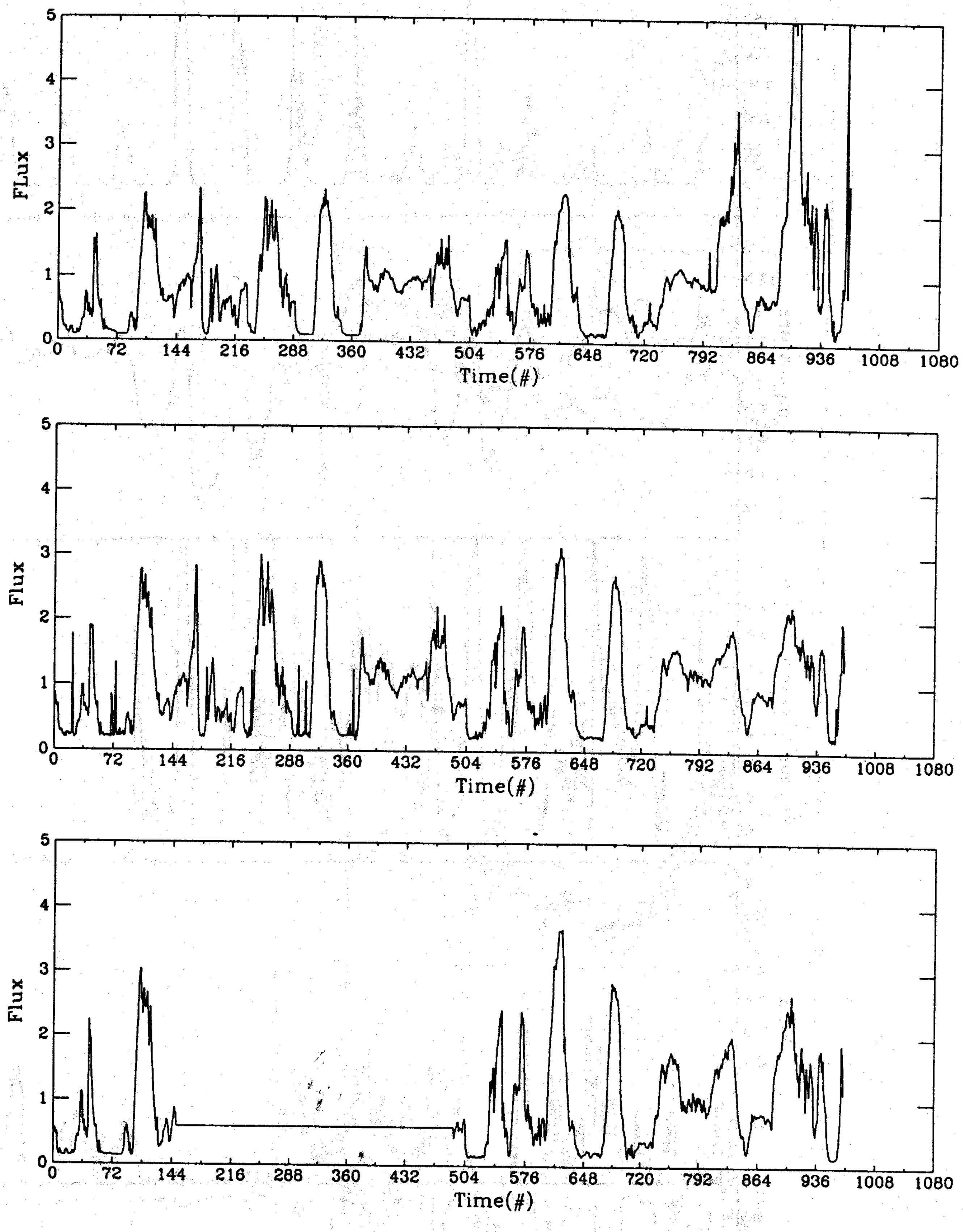
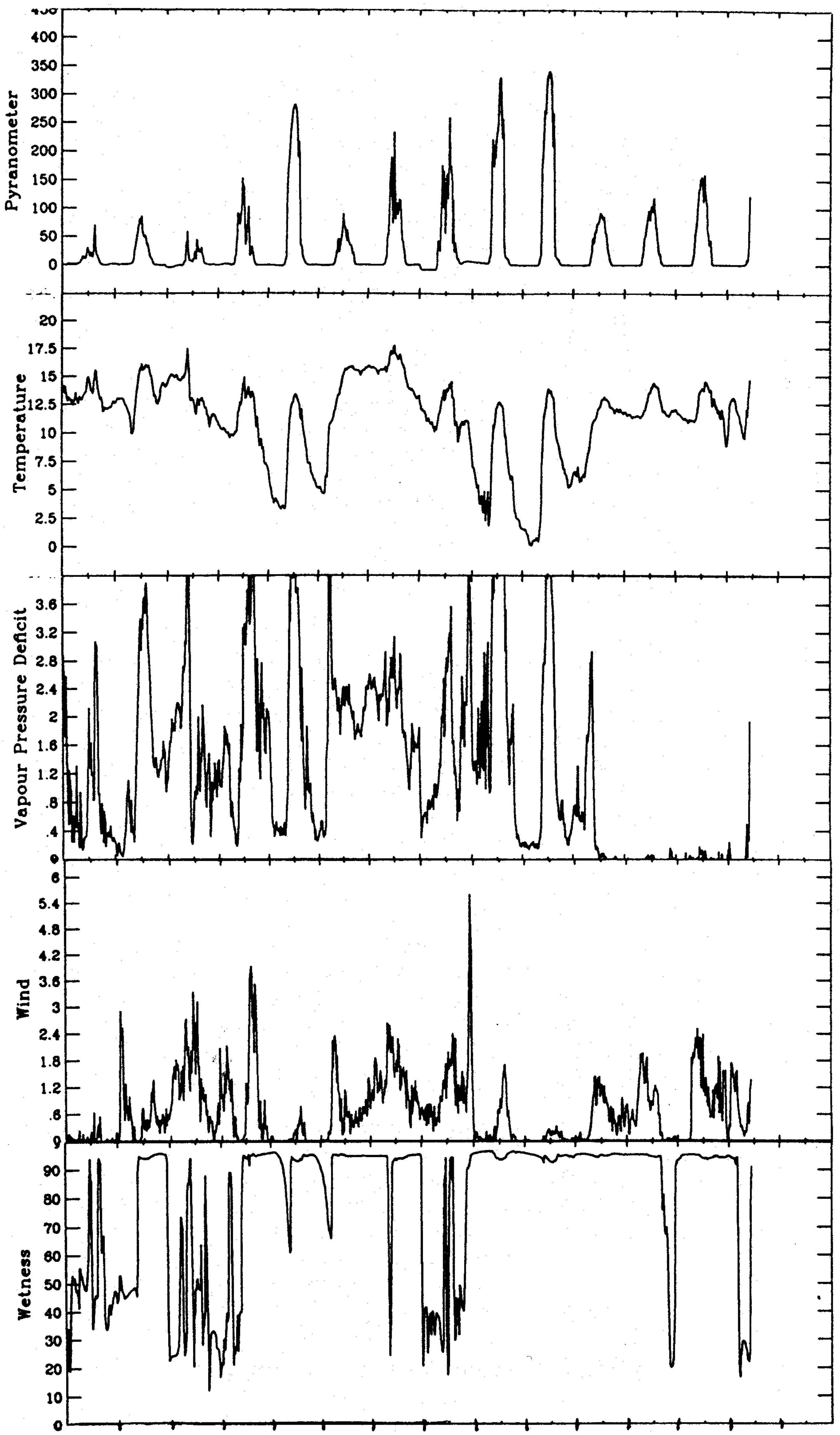


FIGURE 1. Transpiration and weather data for a 14-day period.


Pyranometer
400
350
300
250
200
150
100
50
0
Temperature
20
17.5
15
12.5
10
7.5
5
2.5
0
Vapour Pressure Deficit
3.6
3.2
2.8
2.4
2
1.6
1.2
.8
.4
0
Wind
6
5.4
4.8
4.2
3.6
3
2.4
1.8
1.2
.6
0
Wetness
90
80
70
60
50
40
30
20
10
0

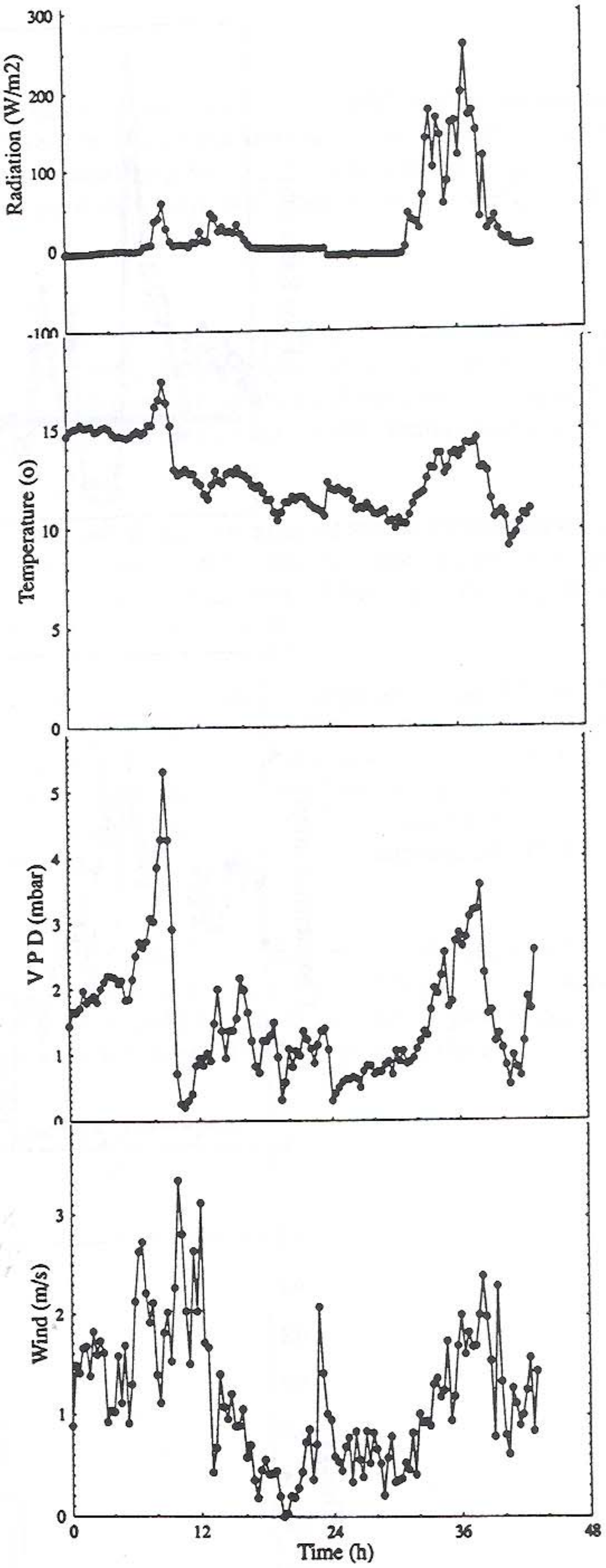
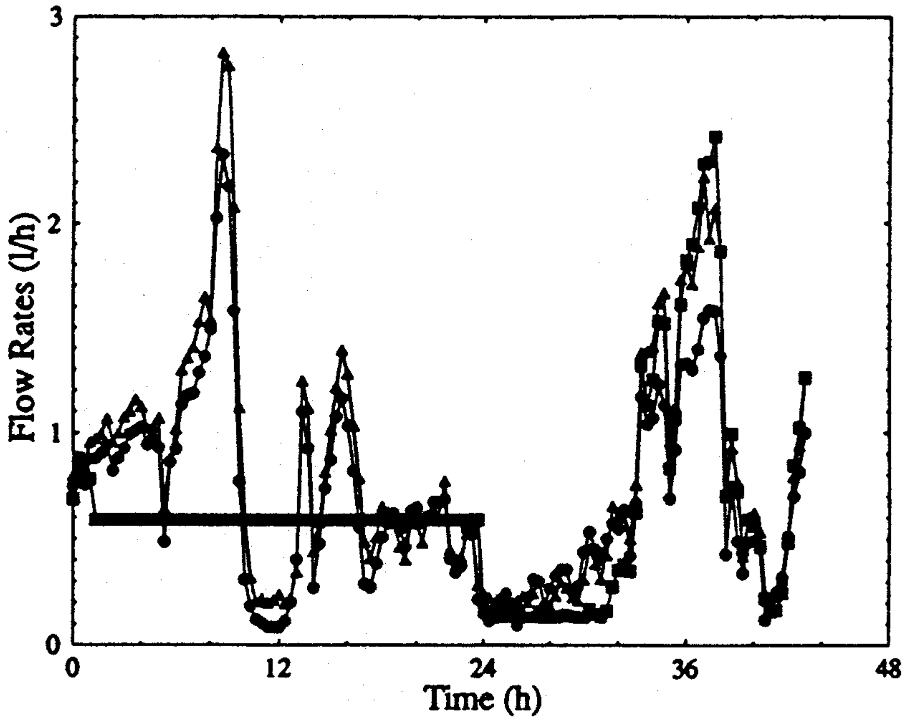
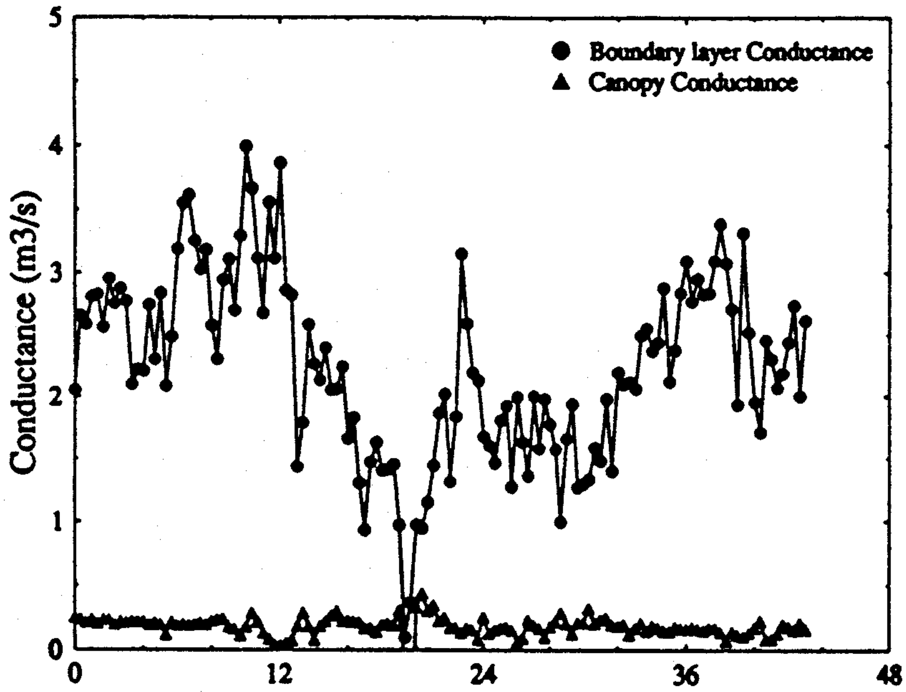


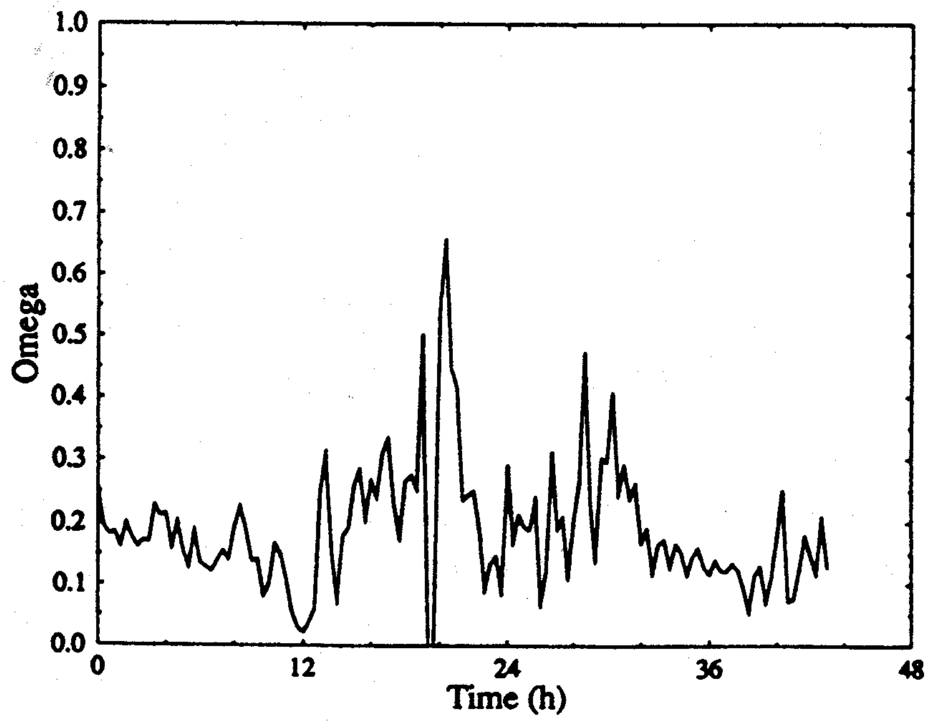
FIGURE 2. **Transpiration and weather data for two days, together with calculated values of canopy- and boundary-layer conductances, and the decoupling coefficient, omega.**



Flow Rates (l/h)
0
1
2
3
0
12
24
36
48
Time (h)



● Boundary layer Conductance
▲ Canopy Conductance
Conductance (m3/s)
0
1
2
3
4
5
0
12
24
36
48



Omega
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
12
24
36
48
Time (h)

The decoupling coefficient was remarkably constant during the 'reliable' daytime periods at about 0.15 - 0.25, indicating the convective component dominated the radiative component of transpiration. This is to be expected considering the isolated nature of the single tree even though the leaf size of poplars is comparatively large which would tend to increase omega.

3.4 Discussion

The three trees gave similar results, and it is clear that a data set from only one could have been extrapolated to the others using the simple measurements of tree canopy size and basal or sapwood area. This presupposes that there are no significant differences in genetic makeup or more broadly, species; that conditions of exposure are broadly similar, and that the soil has the same ability to supply water.

Conversely, multiple measurements back-calculated to canopy or stomatal conductance could reveal specifically, differences between species sites and soil conditions, and species differences in ability to respond to changes in conditions. Obviously the way in which different species react to the onset of drought is of interest.

The results reported here are for well-grown trees exploiting a large root volume of soil which is both deep and well drained. Adjacent plantings on the rather thinner hill soils are much smaller and are more typical of hill country plantings. It is this situation which will repay investigation to show how trees deplete soil water, the extent of reserves available to the tree, the effect of competition with grass and consequent grass production, and the extent to which soil water deficits might carry over into the winter period, with consequent effect on soil stability.

The results show it is feasible to run both heat-pulse equipment and associated weather stations for several weeks at a time in isolated hill country conditions. The calculations demonstrate that simple models can yield data which is more suitable for general conclusions and extrapolation to near-by similar sites and vegetation than -per-tree reports.

PART 11: 4.0 Root Systems

4.1 Preamble

Our objective is to build a set of root distribution data representative of a range of tree species, tree ages, on a variety of soil types. The data is collected from soil cores taken from the rooting zones of selected trees in the field. The data can be used to map distributions of root-length density, positions of woody roots in the various size classes, and by some extrapolation method, patterns of tensile strength within the soil.

4.2 Methods

The three trees used for the transpiration measurements were also used for the investigation into rooting zones.

The rooting zones of the selected trees were intensively cored to a depth of 1 m to a radius of half the inter-tree distances, usually 6-7 m. Two or three adjacent trees were sampled at each site. Each 46 mm core was cut into five or six 100 mm long subsamples in a random, but stratified manner. Roots were then washed from the subsamples and the total root-length of pasture and weed plants, and of trees in a range of size-diameter classes was measured.

Mean root-length densities (cm of root/cm3) were calculated by dividing root length by subsample volumes. Data from individual trees were then pooled as though coming from one representative tree at each site.

4.3 Results

Brief results are given in Figs 3 and 4, which show positions where tree roots were found. Pasture, weeds and rushes are not shown. The most obvious point of interest is the comparatively high number of large woody poplar roots, which contrasts with small numbers seen in other studies of poorly drained sites (not reported here). Large roots seem to have accumulated over time because they were not killed during periodic wet periods.

4.4 Discussion

Fine roots (less than 0.1 mm diameter) make up the vast majority of the total root-system length - probably more than 98%. Although they are present at 1 m in substantial numbers here, this is again in contrast to experience with poorly-drained soils. We consider a substantial number of fine roots (as well as large roots) is desirable at depth if this is to have an effect on increasing soil strength. In the upper regions, soil strength is already enhanced by the presence of herbaceous roots, and additional poplar roots would not be expected to make much difference.

5.0 Final Discussion and Conclusions

This is an initial study which lays the foundation for future work. It has shown that such studies are practical for hill country sites even though access has to be a major consideration to field sites, especially in wet weather. Both transpiration and meteorological measurement

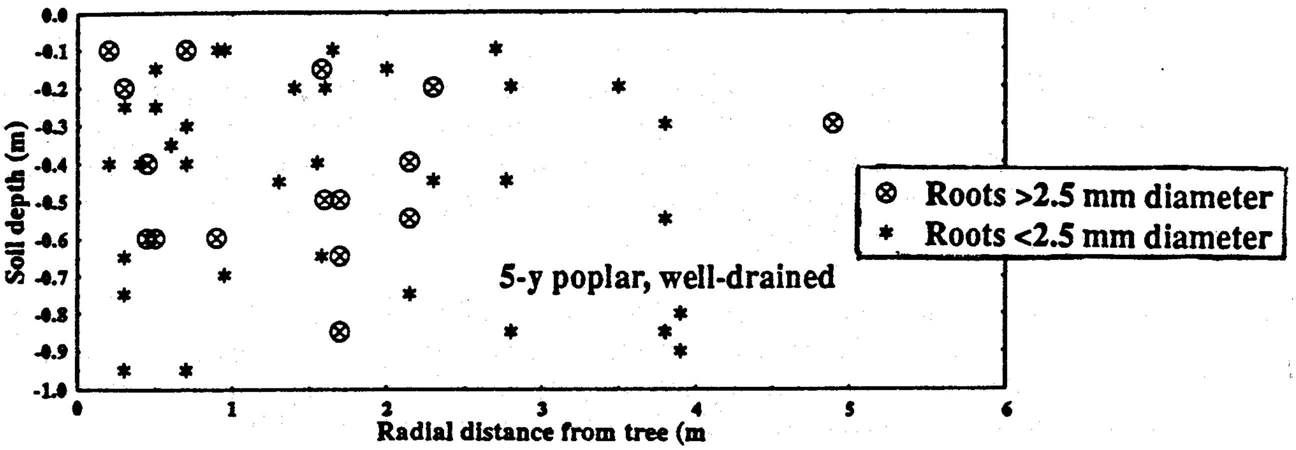


FIGURE 3. Positions of samples containing big (woody) roots.

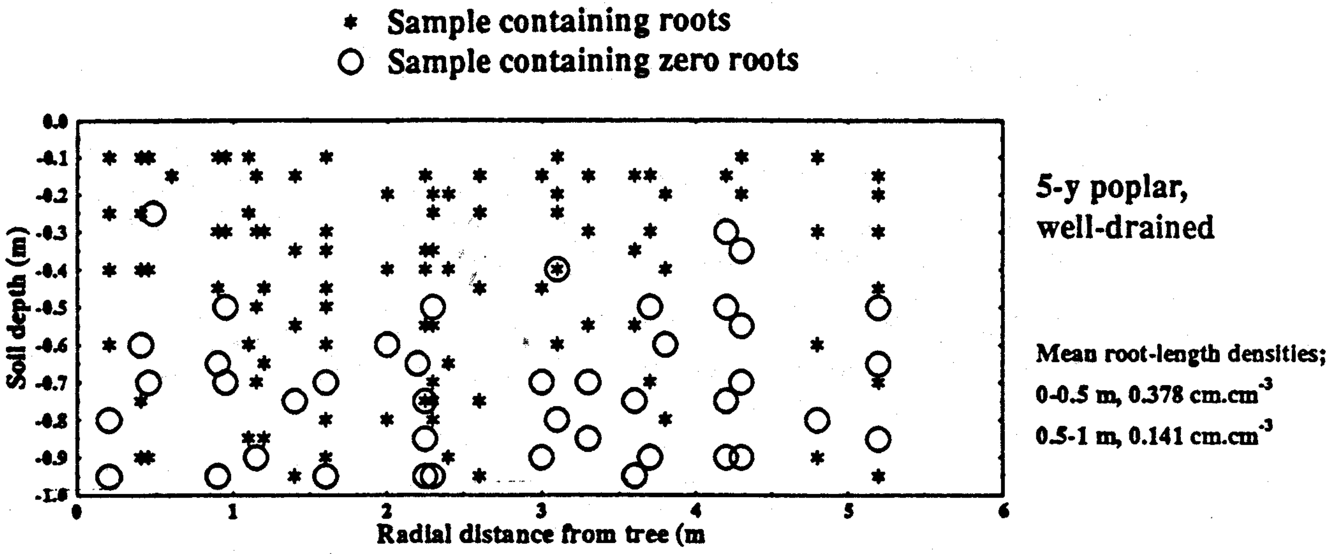


FIGURE 4. Positions of samples containing all roots.

gear worked well in spite of presence of cattle and opossum, which both tend to cause catastrophic damage to poorly protected equipment. Particularly if equipment is expected to work unattended for substantial time periods, this is a major consideration in setting up a site, and should not be underestimated.

Results from those studies showed low variation between similar trees (both species and development) on similar sites. Clearly there is considerable information to be gained from studies which make simple comparisons between species, development, or site. This could be used either to select species characteristics, or to study the effect of vegetation on the site with respect to changes in soil water.

The soil coring study likewise showed that such studies are feasible on sloping topography, and that the amount of replication involved is not excessive. We consider that care should be taken at different sites to ensure sufficient replication, since hill country soil studies show a large amount of inherent variation. This arises largely because of basic erosion processes which have led to the typical New Zealand landscape.

The data we collected from the soil cores is sufficient to characterise the likely effect of root presence on soil stability, given that basic relationships between root reinforcement and increased soil strength can be evolved.

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