# DEPARTMENT OF GEOGRAPHY DISCUSSION PAPER SERIES

GEOGRAPHY

*SOIL LANDSCAPE STUDIES IN THE LOWER FRASER RIVER VALLEY*

*C.B. Crampton*

SIMON FRASER UNIVERSITY
BURNABY BRITISH COLUMBIA, CANADA

# SOIL LANDSCAPE STUDIES IN THE LOWER FRASER RIVER VALLEY

C.B. Crampton

May 1979

Discussion Paper No. 6



Comments are invited.

TABLE OF CONTENTS PAGE

# GEOCLIMATIC CONTROL OF RUN-OFF FROM CHILLIWACK MOUNTAIN

C.B. Crampton

## INTRODUCTION

Igneous and metamorphic rocks are widespread in British Columbia. In many parts of these outcrops the characteristic jointing of these rocks gives rise to a polygonal pattern of surface gullies, defining bed-rock domes. These gullies channel water after a rainstorm, and some aligned gullies become major streams draining mountainous regions. At lower elevations this terrain is potential building land and it is important to consider the possible effects of the geoclimatic regime on any construction activity since the drainage pattern is different from that of many other areas.

Chilliwack Mountain is an area of about 1.2 squ. miles (3 squ. km.), rising abruptly from the Fraser River flood plain to about 1200 ft. (366 m.) in British Columbia. The isolated nature of the mountain made it a convenient study-area. The ridge is composed of andesitic rocks and metamorphosed siliceous (locally calcareous) Middle Jurassic sediments of the Harrison Lake Formation (Roddick, 1965). Like similar rocks elsewhere, the mountain surface is dissected by a polygonal pattern of gullies, reflecting the underlying joint structure (Fig. 1).

The mountain occurs within Krajina's (1969) Douglas Fir Biogeoclimatic Zone, although the original climax stands of douglas fir (with western hemlock and western red cedar) have been logged and burnt, and largely replaced with seral mixedwoods including broadleaf maple, vine maple, white birch and red alder. The mean annual precipitation at Chilliwack is 67 in.

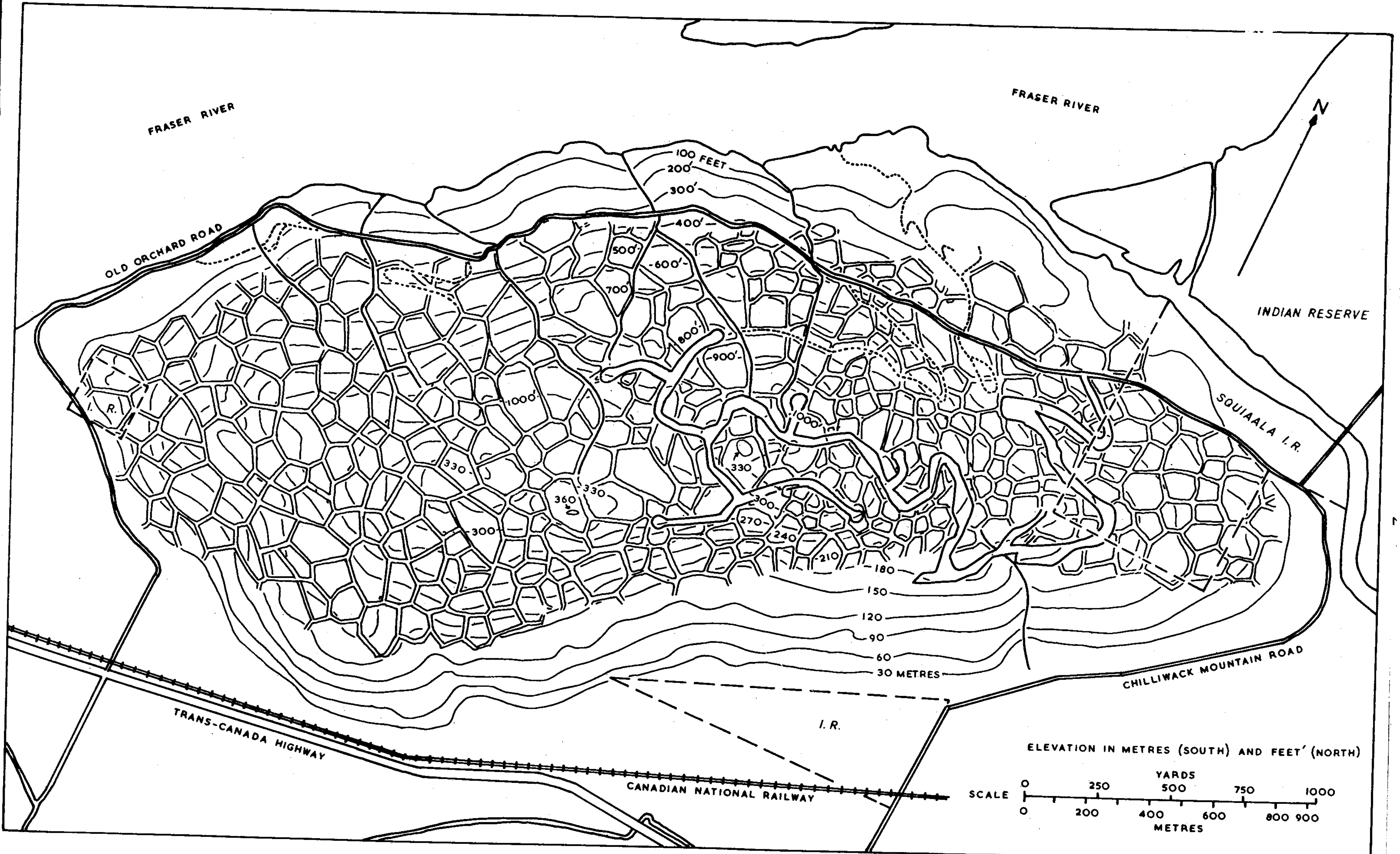


Fig. 1. Topographic map of Chilliwack Mountain, showing distribution of gullies.

(1700 mm.) (Wright, 1966), and according to local reports it is noticeably greater on Chilliwack Mountain.

The possibility of house construction on the mountain plateau required careful consideration of, for example, the siting of septic tanks with regard to soil type and depth associated with the geomorphic landscape. This prompted the study of the natural soil landscape as the hydrological interface between geology and climate. The findings can be applied to other ares of similar rocks and climate where building is taking place.

## PROCEDURE

A field survey of the surficial geomorphology (Fig. 1) and soils of the mountain was aided by the use of very large scale (1:7000) air photographs. Using the method of Gumbel (1954), extreme value frequency analysis (Fig. 2) was undertaken for precipitation data from the Chilliwack area, supplied by the Resource Analysis Branch, British Columbia Ministry of the Environment.

## PHYSIOGRAPHIC ENVIRONMENT

The southeast slope of the mountain down to the flood plain is steeper than the northwest slope, which drops to the Fraser River (Fig. 1). The rolling plateau top slopes gently northwest. The igneous and metamorphic rocks are generally severely fractured near the land surface. A polygonal joint pattern, the polygons varying in diameter between about 88 yrds. (80 m.) in the more finely crystalline andesitic rocks, and about 220 yrds. (220 m.) in the more coarsely crystalline meta-sediments, dissects the mountain plateau, expressed at the land surface by a network or gullies defining bedrock domes (fig. 1). The gullies channel water after a rainstorm, and some aligned gullies have become major, though intermittent streams draining the mountain. The gully network is sufficiently dense to provide many possible alternative drainage channels if one is blocked.

There is loess and till on the mountain plateau, thin and porous over fractures and joints on polygon domes, and thick on gully sides. The surficial deposits on polygon domes are parent materials to Orthic Eutric Brunisols (Clayton et al., 1977), and on the gully sides to Gleyed Gray-Brown Luvisols. The normally dry gully bottoms are often swept clear of soils and stony. Clay has been translocated down the deeper soil profiles on gully sides, to accumulate in the lower profile and form a distinctly clayey zone about 12 in. (30 cm.) thick where the profile merges into the underlying fragmented rock. Percolating rainfall accumulates as a perched water table over this clayey illuvial horizon, producing faint color mottling in the lower profile, indicative of imperfect drainage.

Whereas rainfall passes freely through the Brunisols on the bedrock polygon domes to join the water table, the clayey subsoil of the Luvisols on gully sides impedes downward percolation, and some water flows downslope through appropriately aligned gullies to the footslopes of the mountain. The catchment area is small and run-off is rapid. During the summer most gullies are dry, except after the occasional rainstorm. Frequent winter storms across the mountain during October to February generally keep the water table high and water flowing in the major gullies throughout the winter. This flow varies from a trickle most of the winter,

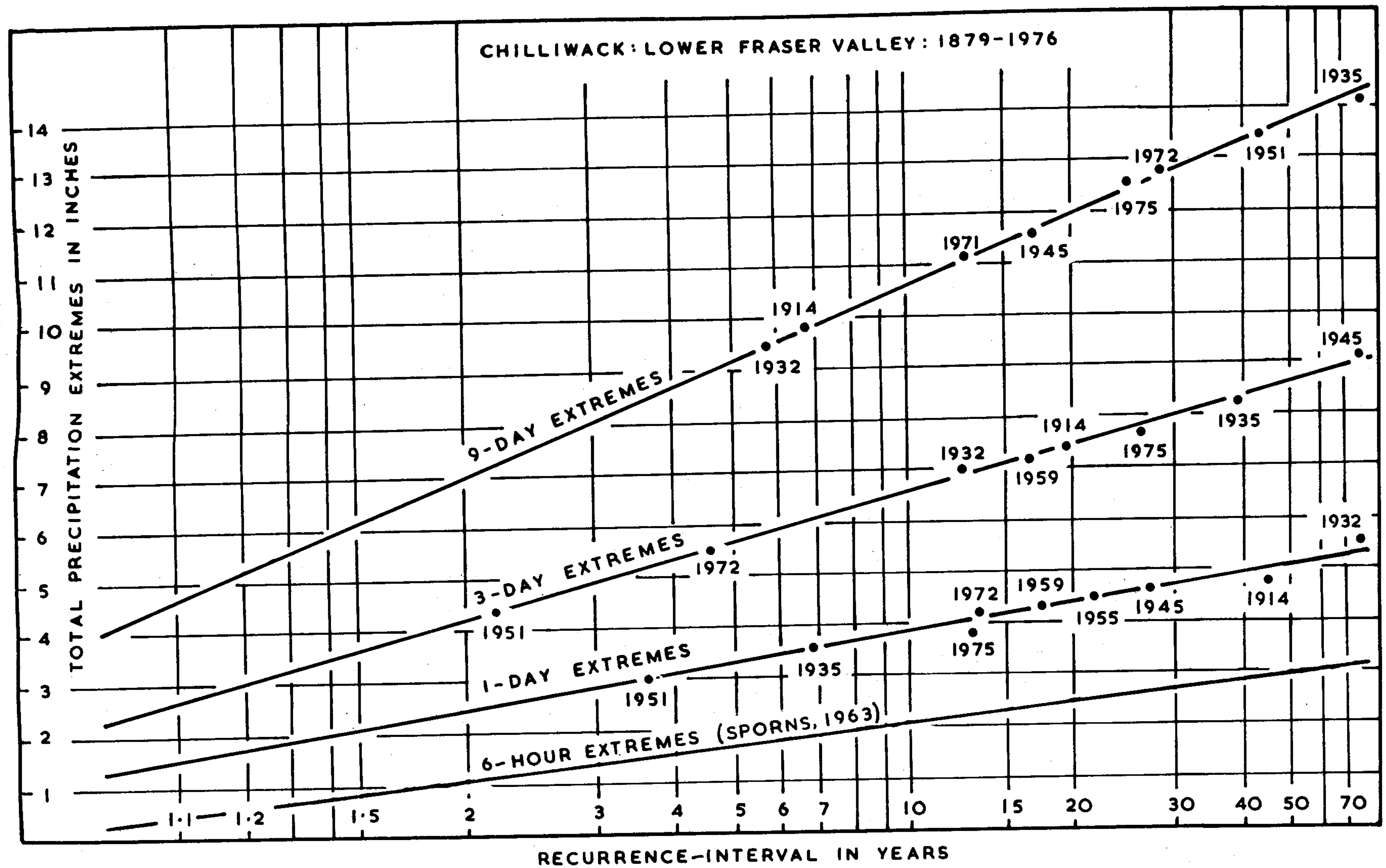


Fig. 2. Gumbel analysis of data from the Chilliwack area.

to a torrent during and, for a short while, after a storm.

INTERPRETATION

Like other weather phenomena, rainfall is characteristically non-cyclic and highly irregular in terms of duration and amount. Extreme value frequency analysis devised by Gumbel (1954) was used to calculate the recurrence-interval for rainfalls of different magnitudes and duration around Chilliwack, for the period between 1879 and 1976. The reasonably linear scatter on Gumbel graph paper for selected years is shown (Fig. 2). The 1935 January one-day, three-day and nine-day total rainfall amounts were 3.5 in. (89 mm.), 8.3 in. (211 mm.) and 14.2 in. (361 mm.). The nine-day period included the three-day period, which included the one-day period. These rainfall amounts were associated with increasingly longer recurrence-intervals of 6.9, 39 and 81 years, respectively (Fig. 2). Thus, the exceptional amount of rainfall that fell during the nine-day period in January of 1935 can be expected to occur, on average, once every 81 years; in other words it is an unusual event. However, the recurrence-interval is only an average and such excessive rainfall might occur again next year. Also, implicit in this style of analysis is that sooner or later an even greater nine-day rainfall total will occur although, on average, such a disaster will be associated with a much longer recurrence-interval. The three-day and one-day rainfall totals are successively more common events, associated with decreasing recurrence-intervals.

The rate of rainfall for this inclusive sequence of periods during January of 1935 was 0.15 in. (3.7 mm.) per hour for the one-day period, 0.12 in. (2.9 mm.) for the three-day period, and 0.07 in. (1.7 mm.) per hour for the nine-day period, a declining rate even though the recurrence-intervals were increasing and the total rainfall was becoming an increasingly rare event. The declining rate of rainfall with increasing time interval would, therefore, be even more pronounced in cases where the magnitude of rainfall and the recurrence-interval declined in the sequence from one to nine days, as occurred during February of 1932 and January of 1914 (see Fig. 2). Thus, although the total amount of rainfall during an exceptional nine-day period is very great, the excessive downpour associated with a shorter period is never maintained for longer periods of time.

Sporns (1963) calculated the recurrence-intervals for six-hour storms of different magnitudes within the same Chilliwack area (Fig. 2). The interpretation of Gumbel analyses becomes less accurate as the recurrence-interval increases because of the nature of the graph paper required to produce a reasonably linear scatter. An analysis achieves its greatest utility at less than the total period of the records, for example 25 years or less. The rate of rainfall associated with a recurrence-interval of 20 years is 0.39 in. (10 mm.) per hour for a six-hour storm, 0.18 in. (4.6 mm.) for a one-day storm, 0.10 in. (2.7 mm.) for a three-day period of rainfall, and 0.06 in. (1.4 mm.) per hour for a nine-day period of rainfall. At similar recurrence-intervals, the rate of rainfall decreases noticeably with increasing storm duration.

Within Gumbel analysis the most probable storm has a recurrence-interval of 1.6 years. On average, the most probable one-day storm can be expected to drop about 0.09 in. (2.3 mm.) of rain per hour on Chilliwack

Mountain, the one-day storm with a recurrence-interval of five years 0.14 in. (3.6 mm.), ten years 0.16 in. (4.1 mm.), 15 years 0.18 in. (4.6 mm.), and 20 years 0.19 in. (4.8 mm.) of rain per hour. A similar relationship holds for rainfalls with the different durations illustrated in Fig. 2. Thus, the exceptionally violent storm associated with a long recurrence-interval can be expected to drop about twice as much rain onto the mountain as the most probable storm.

The rainfall amounts are based on data collected at Chilliwack, situated on the Fraser River flood plain near Chilliwack Mountain. A comparison with other isolated mountains with a similar elevation above the surrounding land and for which there is more complete precipitation data suggests that the rainfall amounts over the mountain top are at least one and a half times greater than the amounts associated with the footslopes.

DISCUSSION

The exceptional long-duration rainfall associated with a long recurrence-interval can drop a great quantity of rainfall upon Chilliwack Mountain, raising the water table to high levels to produce continuous water flow in the major aligned gullies draining the mountain. The pore water pressure can be increased in the subsoil and loose substrata to the point that surficial landslips can occur, as recalled by local residents, for example during 1951 (see Fig. 2) when a slide occurred on the SSW slope, still clearly visible today. Slides that occurred on the slopes during 1935 have revegetated.

The exceptional short-duration storm associated with a long recurrence-interval can drop rain upon Chilliwack Mountain at a very great rate, locally exceeding the capacity of the soils to transmit this water down to the water table. This produces torrential flow in many of the gullies, in some that do not carry any water during the most probable storm, as vividly remembered by local residents during 1975 and 1972 (see Fig. 2). These storms swept many gullies clear of soil to leave a stony pavement. The excessive run-off was channeled into aligned gullies onto the footslopes where catastrophic gully erosion and deepending occurred locally. Earlier short-duration storms are less clearly recalled, although the irregular occurrence of such events is part of the local folklore. The dense gully network allows many other drainage routes to develop if one route is blocked, for example, by deadfall. Hence, there is a strong element of unpredictability associated with run-off after the occasional violent storm. Such storms, the unpredictable run-off and the accompanying gully erosion have threatened houses on the footslopes with destructions.

Where the terrain is unsuitable for normal sewage disposal systems (Bender, 1971), the seepage pit can be constructed. The effluent from the septic tank flows into a large pit with a porous lining through which the effluent seeps into the surrounding soil. A sewage disposal system, particularly the seepage pit, will fail if the depth of soil is inadequate, or if the volume of soil around the pit is insufficient to absorb and thoroughly decompose the effluent. The soils on Chilliwack Mountain are generally shallow. Then the effluent will enter and pollute the ground water. A sewage disposal system will fail if the clay content of the surrounding soil is too great, producing poor drainage and inhibiting decomposition of the effluent. It will fail if there is some kind of impervious layer in the soil, restricting penetration and decomposition of the effluent. The gully slopes carry deeper soils than elsewhere, but often with a clayey subsoil impeding percolation of fluids. A sewage disposal system will fail on slopes. Chilliwack Mountain is rocky terrain with abundant slopes, and on the plateau where building would take place it is dissected with a reticulate gully pattern. In the latter cases the effluent might well reach the land surface, smell, attract flies and become a source of disease. Thus far, slopes, shallow soils and an impervious layer all constitute local impediments to a sewage disposal system.

The gullies probably constitute the best available sites for sewage disposal systems, if good quality fill is trucked in to create a sufficiently great volume of soil for adequate decomposition of the effluents. In the past some gullies have been choked with deadfall, or a road berm. After an exceptional downpour, ponding can occur behind such barriers. Unless very careful site inspection is carried out, such ponding could disrupt the surroundings to a seepage pit and carry still undecomposed effluents downslope.

# SOIL CLIMATE OF MATSQUI PRAIRIE

C.B. Crampton

## INTRODUCTION

Matsqui Prairie is a section of gently undulating floodplain enclosed between a meander of the Fraser River and Matsqui Slough (Fig. 3), in the Lower Fraser Valley of British Columbia. The maritime climate is associated with a mean annual precipitation of 1700 mm (Wright 1966). The study-area has been completely cleared for agriculture, and the alluvial textures range from silts to sands. Temperature profiles have been measured in these soils, with the objective of relating spatial and temporal changes of temperature to environmental factors.

## PHYSIOGRAPHY

At some time in the past the flood plain was moulded into a parallel ridge and trough landform distinctly different from the point-bar scrolls normally associated with a meander loop. The orientation of this ridge and trough landform is not everywhere sensibly related to the present river meander (Fig. 3). There is an approximately three metre amplitude of relief between ridge and trough, with the flood plain undulating from about 7.5 m at its highest near the centre of the study-area, down to the Fraser River.

A plough pan has developed in many parts, but especially in the east of the study-area, this pan being associated with all soil textures and states of internal drainage. The hard, compacted soil of the pan extends down from the base of the plough layer to between 20 and 50 cm. It was noticeably difficult to penetrate with an auger after long dry periods.

Other work (eg. Saini and Hughes 1972) indicates that some crop yields can be affected by such a plough pan, but on the Matsqui flats only local interference to the penetration of rainfall or roots could be attributed to the pan.

Well drained, sandy, loamy or silty soils occur on the ridges, grading downslope into less well drained, silt loam over silty clay soils in the troughs. Well drained and moderately well drained soils are mostly Orthic Eutric Brunisols (Clayton et al. 1977), whereas imperfectly drained soils are mostly Gleyed Gray-Brown Luvisols and poorly drained soils Eluviated Gleysols. On the small scale, better drained soils dominate on higher land near the centre of the study-area, and locally on levee-type banks and dykes alongside the Fraser River, whereas poorer drained soils occur mostly alongside Matsqui Slough and in broad depressions on the flood plain (Fig. 3).

PROCEDURE

A temperature probe was used to measure the daytime soil temperatures at depths of 0, 10, 20, 30, 40 and 50 cm below pasture lands, at 150 sites distributed across the ridge and trough topography, during June and July of 1978. Augering allowed the distribution of textures to be hand-estimated down through each profile, the determination of the thickness of the compacted plough pan below the plough layer, and the field-interpretation of internal soil drainage based primarily on colour and mottling horizonation.

The temperatures associated with particular types of soil profiles, made at certain times of the day, separated according to prevailing

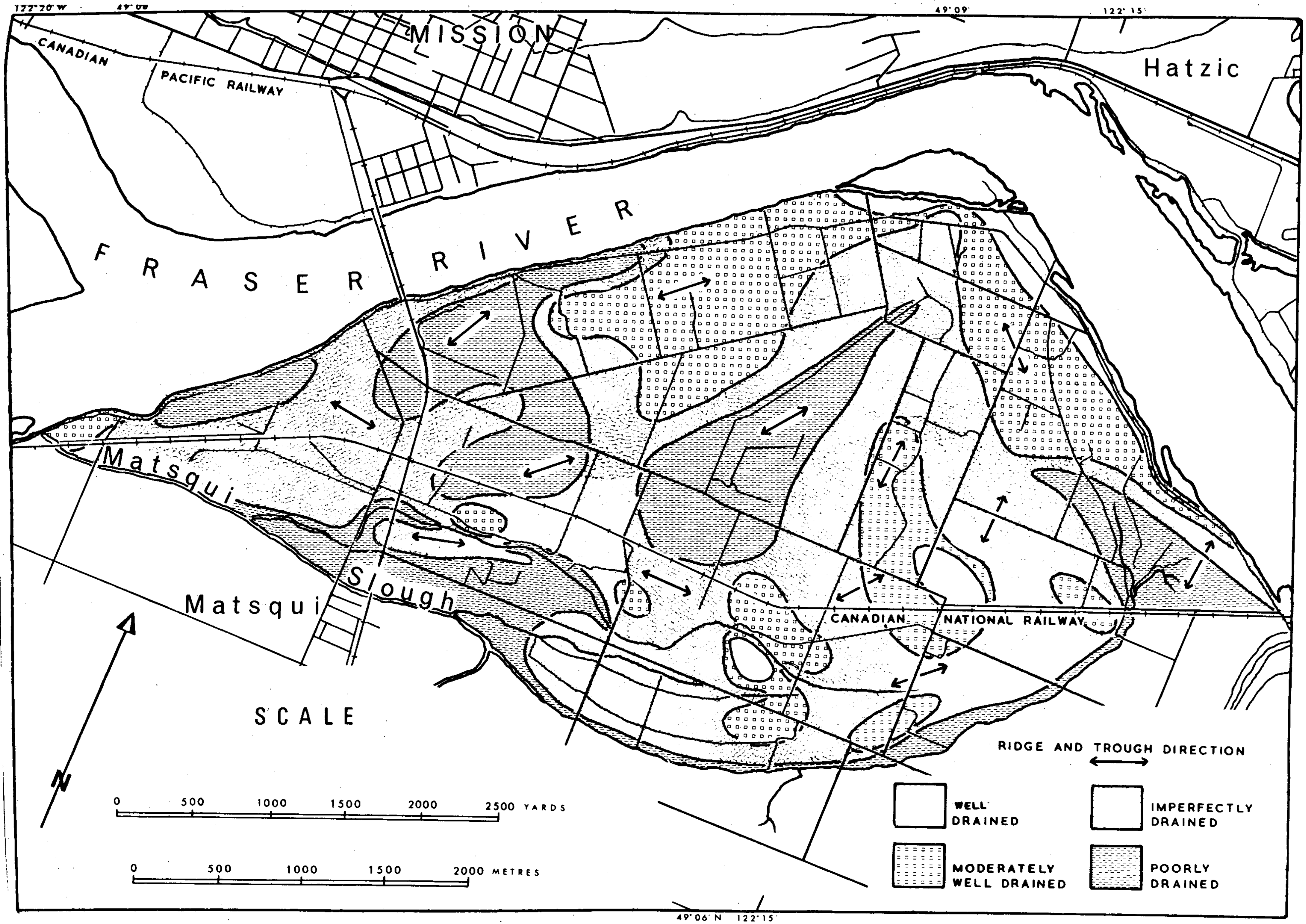


Fig. 3. Distribution of soil drainage classes on Matsqui Prairie, and orientation of ridge and trough topography.

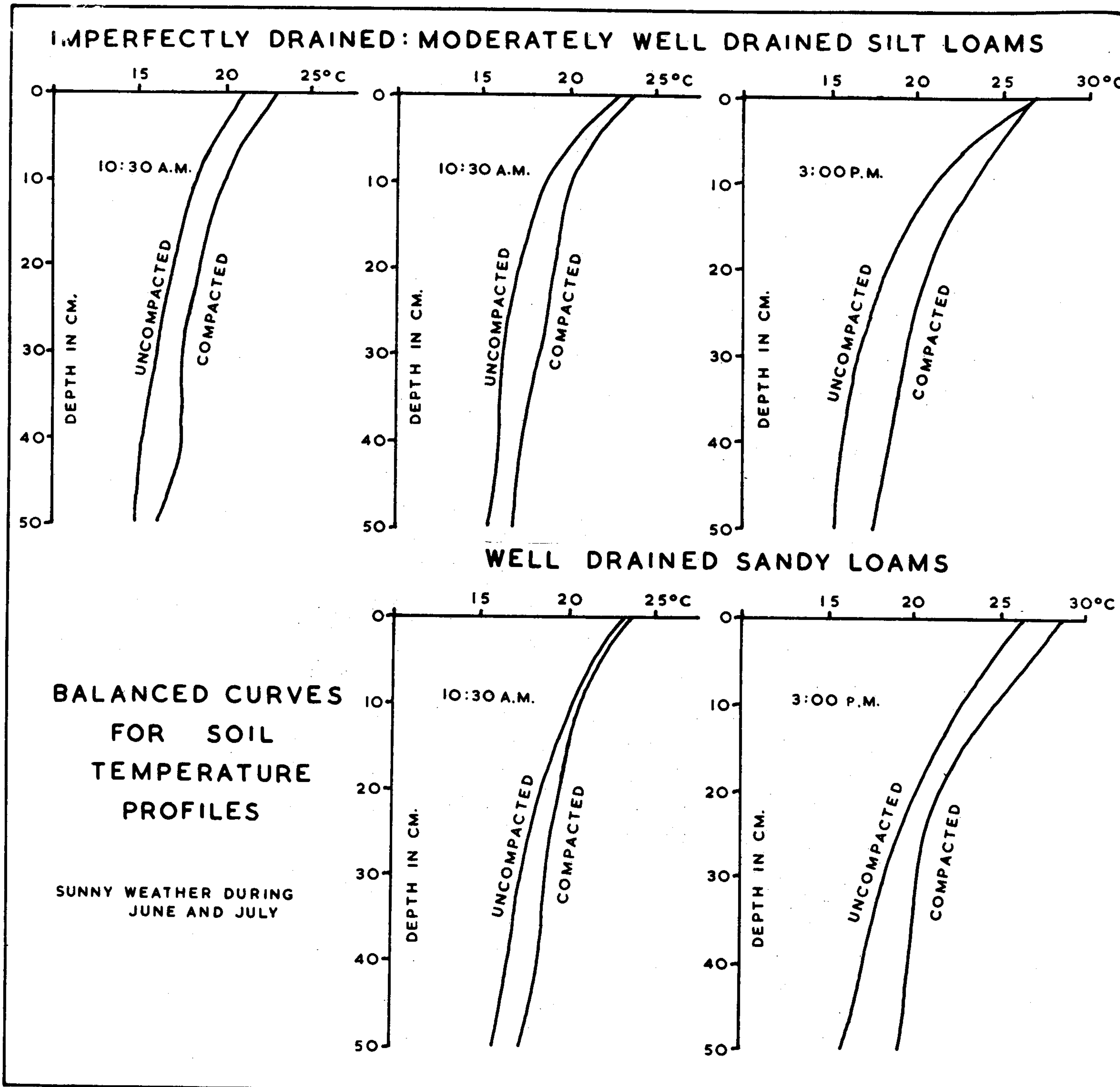


Fig. 4. Balanced curves for soil-temperature profiles.

conditions, were plotted and balanced curves drawn through the scatter in order to show the average change in soil temperature down through the profiles (Figs. 4 and 5). Since changes of soil temperature with depth are generally exponential (Oke 1978, Geiger 1973), each scatter was analysed for the best exponential fit, and various statistics including the $r^2$-value have been tabulated (Fig. 6).

RESULTS

During sunny weather the soil temperatures decreased rapidly from the land surface down through the topmost 10 to 20 cm of the profile (that is the lapse rate showed a strong negative gradient), and slowly down below these depths (there is a weaker gradient) (Fig. 4), as also reported by Geiger (1973). During the morning in the troughs, compacted imperfectly drained silt loams were warmer throughout the profile than uncompacted, but otherwise similar soils (Fig. 4). While the average temperature was constant between 30 and 40 cm in the compacted soil, to produce this average constancy, in some profiles during the morning the subsoil between these depths was actually warmer than above and below, and there was a positive gradient.

Similar observations were made during the morning in moderately well drained silt loams (Fig. 4) on ridge slopes or crests, except that surface temperatures were slightly higher than in imperfectly drained soils, and there was a greater difference between compacted and uncompacted profiles except at the surface. In the latter silt loams the same high surface temperatures of about 27°C were achieved during the afternoon in both compacted and uncompacted profiles.

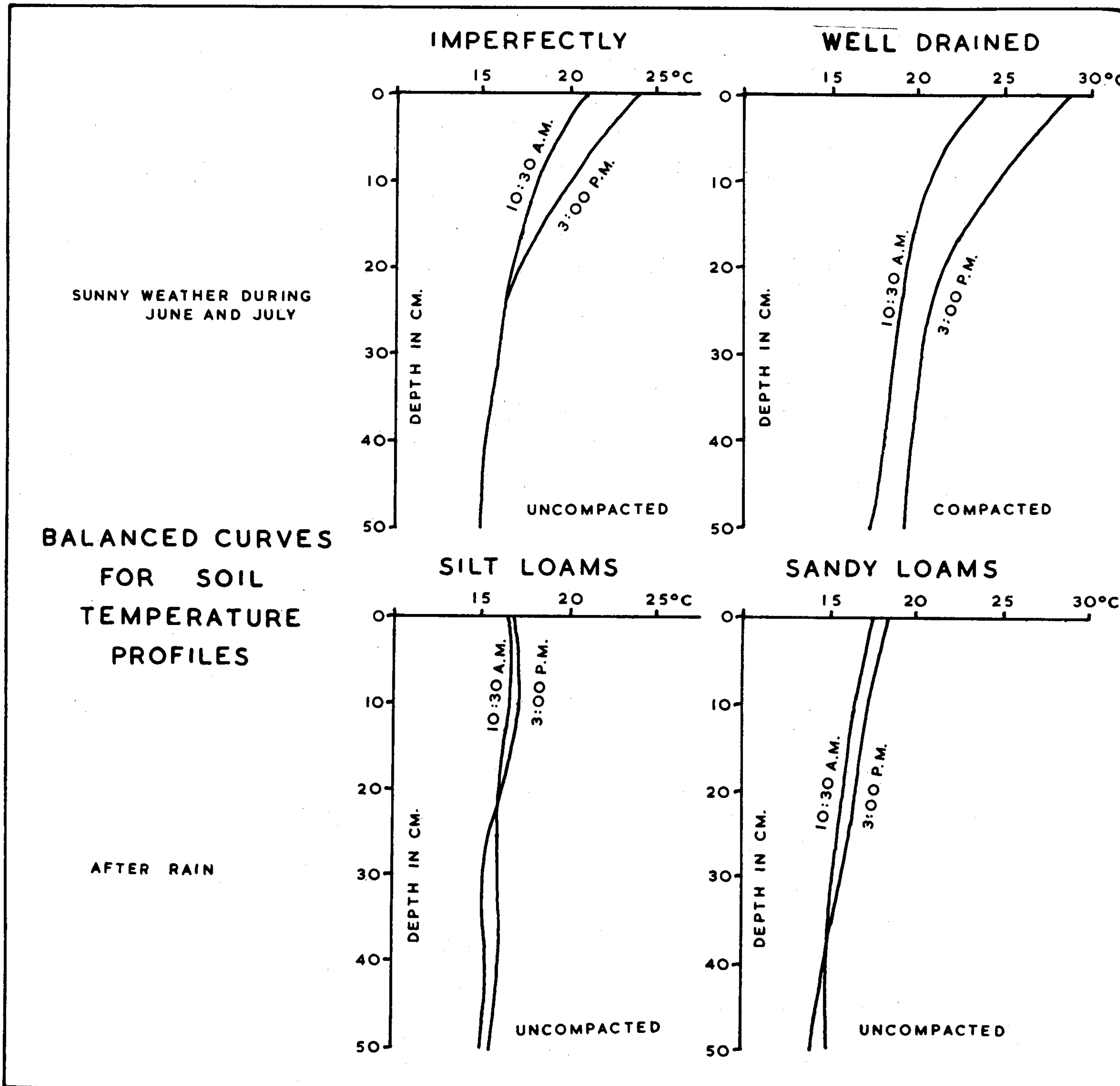


Fig. 5. Balanced curves for soil temperature profiles.

Where well drained sandy loams were present on ridges, the least difference in surface temperatures between warmer compacted and cooler uncompacted profiles was observed during the morning, and the greatest difference during the afternoon (Fig. 4), the opposite relationship to that observed in silt loams. Surface temperatures in sandy loams were also greater than those in silt loams, reaching about 29°C during the afternoon. However, as observed in other profiles, in some compacted sandy loams between 30 and 40 cm depths the temperatures were actually warmer than above and below, but the positive gradient was less pronounced than for silt loams.

The greatest difference between the morning and afternoon temperatures of both uncompacted imperfectly drained silt loams, and compacted well drained sandy loams (Fig. 5), occurs from near the surface to about 20 cm. Below 20 cm there is no difference between morning and afternoon temperatures within the imperfectly drained silt loams, but a certain difference between morning and afternoon temperatures is maintained below 20 cm in well drained sandy loams.

After rain there is little difference between morning and afternoon temperatures in both imperfectly drained silt loams and well drained sandy loams, except that afternoon temperatures were marginally warmer near the surface (Fig. 5). Below 20 cm in imperfectly drained silt loams the afternoon temperatures had actually cooled slightly below the morning temperatures at these depths. Compared with the morning temperatures, the cooler afternoon subsoil temperatures were observed below the greater depth of 40 cm in well drained sandy loams.

## INTERPRETATION

The total thermal response of a soil is proportional to its thermal conductivity (its capacity to transmit heat), and its heat capacity (the amount of heat required to raise the temperature of unit volume by one degree), combined within a measure called thermal diffusivity. All of these measures are affected by the same soil factors, but not necessarily to the same extent.

The thermal conductivity is greatest for sands, and it decreases through silts and clays which have a greater heat capacity (Geiger 1973). Hence, the subsoil between 20 and 50 cm in uncompacted sandy loams was warmed to higher temperatures than in uncompacted silt loams during the afternoon of sunny days (Fig. 4), although the surface temperatures of both textured soils were about the same 27$^{o}$C. Although wet for much of the year, imperfectly drained profiles had mostly dried out by mid-summer. Below the silt loam topsoil the subsoil of imperfectly drained soils was generally a silty clay. Therefore, the penetration of heat down into the profile was least for these soils (Fig. 5). Under sunny skies the warming effect did not penetrate beyond 25 cm, the common transitional boundary between topsoil and subsoil.

It follows from the evidence that a warming interface penetrated down into the soil during the day, followed by a cooling interface during the night. The occurrence of warmer morning temperatures between 30 to 40 cm than above and below, particularly in some silt loams but also in some sandy loams, suggests the retention through the night of warmth that penetrated the subsoil during the previous day. Heat disperses more slowly in

Sunny weather during June and July

| texture and drainage | time | compacted | N | mean $^{o}C$ | standard deviation | $r^2$ |
|---|---|---|---|---|---|---|
| silt loam imperfect | 10:30 am | no | 102 | 16.8 | 2.81 | 0.53 |
| | | yes | 102 | 18.7 | 2.89 | 0.60 |
| silt loam imperfect | 3:00 pm | no | 102 | 17.3 | 2.82 | 0.62 |
| silt loam moderate | 10:30 am | no | 102 | 17.5 | 2.45 | 0.66 |
| | | yes | 84 | 19.3 | 2.78 | 0.64 |
| silt loam moderate | 3:00 pm | no | 102 | 18.4 | 4.01 | 0.55 |
| | | yes | 84 | 20.9 | 3.74 | 0.60 |
| sandy loam well | 10:30 am | no | 102 | 18.3 | 2.83 | 0.65 |
| | | yes | 60 | 19.8 | 4.14 | 0.50 |
| sandy loam well | 3:00 pm | no | 102 | 20.5 | 3.76 | 0.79 |
| | | yes | 42 | 22.0 | 4.02 | 0.60 |

Fig. 6. Best exponential fit for selected soil-temperature data.

silty soils.

Soils can be compacted by agricultural operations, particularly when wet since the greatest changes in bulk density occur when soils have a higher moisture content (Harris 1971). Also, the greatest settling occurs in medium-textured soils. As well as having a greater bulk density, compacted soils have a concomitantly greatly reduced pore space, holding much less air than uncompacted soils. Aeration of soils depends primarily on the large pores that drain quickly after rainfall, and compaction destroys many of these large pores (Grable 1971). The thermal conductivity of still air is very much lower than for the different textured soil materials. Hence, compared with uncompacted soils, compacted soils, whether slightly moist silt loams or sandy loams, are warmed to higher temperatures throughout the profile by the afternoon of sunny days (Fig. 4), consistent with the increased thermal conductivity accompanying an increase in bulk density reported by Willis and Raney (1971). In this study compacted sandy loams underwent the greatest warming effect, mostly above 25 cm (Fig. 5).

Compacted silt loams conduct heat more rapidly than uncompacted silt loams. Hence, there has been a greater transference of heat away from the surface and into the profile for the compacted silty soils compared with the uncompacted soils. Thus, surface temperatures are the same, but subsoil temperatures for the compacted soils are greater (Fig. 4). Because a sandy loam conducts heat more rapidly than a silt loam, there has been a greater sub-surface heating of the uncompacted and, especially, the compacted sandy loams (Fig. 4). The surface temperatures for the compacted sandy loams are greater than for the uncompacted profiles, presumably because there is less difference in their conductivities compared with silty soils. At depths below 30 cm the temperature gradients in compacted and uncompacted sandy loam profiles diverge as much as for silty profiles.

Water added to a soil increases its thermal conductivity, dispersing heat added to the topsoil rapidly through the subsoil. Also, water entering a soil lowers the temperature because of evaporation. After rain, the topsoil temperatures were more moderate compared with dry soils, the afternoon temperatures being only about 17°C for silt loams, and only about 18°C for sandy loams (Fig. 5), consistent with work reported by Geiger (1973). As the warm interface penetrated down both textured profiles through the day, the subsoil cooled marginally probably by evaporation, at a depth of about 20 cm in silt loams and about 40 cm in sandy loams by the afternoon.

## CONCLUSIONS

As would be expected, sandy soils warmed more quickly during sunny days than silty soils. Soil temperatures decreased rapidly down from the land surface, particularly in silty soils because of their lesser thermal conductivity compared with sandy soils. A warming interface migrated down into each soil profile through the day, and a cooling interface during the night. Sometimes, the cooling interface failed to nullify the subsoil temperatures warmed during the previous day, to produce an inverted temperature gradient during the following morning. Because of a reduction of thermal insulation resulting from the restriction of pore space in compacted soils, the latter profiles warmed up more quickly to a greater depth than uncompacted soils. Heat was conducted away from the surface of compacted silty soils faster than in sandy soils, whether compacted or uncompacted. After rain, as the warming interface migrated down the soil profile, evaporation cooled afternoon subsoil layers below those of the morning.

This study confirms the widely experienced more rapid warming of sandy soils compared with silty or clayey soils. The study reveals that a compacted plough pan also increases the warming effect, whether in silty or sandy soils. For shallow rooting crops a warm, compacted subsoil could be advantageous. Soil temperatures are probably more critical (Trouse 1971) for plants with deep rooting. A compacted soil has advantages as a heat bank.

# ANALYSIS OF SYNERGISM FOR MODELING INTERNAL SOIL DRAINAGE

## INTRODUCTION

Synergism is a concept that describes the interaction of independent variables with a combined effect much greater than if each variable (or synergist) was acting separately. A synergist then, though possibly without major effect in itself, greatly enhances a process in conjunction with other synergists. In practice, the application of this concept has been limited to certain fields so far, for example pestology and pharmacology. Some research into the biochemistry of insecticides has been directed towards finding compounds which act as synergists, such that the effect of an insecticide is greatly enhanced, beyond the sum of the effects of the synergist and insecticide applied separately (Wilkinson, 1976).

Similarly, drug interactions may be synergistic when the combined effects resulting from their concurrent use results in a greatly exaggerated effect compared with the effects of their separate use (Goodman and Gilman, 1970). Thus, as a relatively innocuous example, coffee on its own has little effect on a headache, but acts as a type of catalyst when taken concurrently with acetylsalicylic acid, to greatly enhance the soothing effect of the latter.

Just as variables can combine to enhance the total effect, it follows that they could also combine to reduce the total effect below that produced by the variables acting separately, a process called negative synergism or antagonism. One objective of this research is to devise a method for analyzing antagonistic as well as synergistic interactions between independent variables over their full range of effects on a particular dependent variable.

Many research projects are structured entirely to produce input data for statistical analysis. Most field surveys are conducted on a much more extensive scale and use terrain factors which are not especially suitable for orthodox statistical analysis. Terrain factors which are part of a field survey allow the surveyor to use experience to expedite an interpretation of a relatively large area. Unfortunately, such environmental variables can neither be measured precisely and linearly, nor do they have the independence assumed in orthodox statistical analysis.

Another objective of this study is to use as independent variables terrain factors which are a normal part of field surveys. An analysis of synergism between these factors should facilitate a greater understanding of the influences on the dependent variable. The method is intended for general application within the subjective field of landscape interpretation on the assumption that synergism permeates all such environments, and that its elucidation is essential in any analytical work based on the field. It is intended that the analysis should support and not replace a field survey.

Specifically, this study concerns interactions between terrain factors affecting internal soil drainage (as distinct from the surface drainage of a region). The drainage varies from well drained (the synergistic effect) to poorly drained (the opposite or antagonistic effect), within a specific area, the Green Timbers Research Forest in the Lower Mainland of British Columbia. The independent variables used were those involved in routine field work for the production of a map (Fig. 7). Soil profile pits were dug and the profile characteristics were recorded at 425 sites distributed systematically on a grid basis across the study-area for analytical purposes and, albeit supported with this information, the area was surveyed using normal field methods of landform and site inspection interpretation.

Because of the nature of the input data, it is essential that the results of the analysis are checked with an independent sample.

## PHYSIOGRAPHY OF STUDY-AREA

The Green Timbers Research Forest is situated in Surrey south of the Fraser River in Greater Vancouver, British Columbia. The area of 109 hectares is mostly mixedwoods, although roads, a power line and forest school activities have encroached on the forest. The forest species include douglas fir, western hemlock, western red cedar, broadleaf maple and vine maple. The terrain undulates gently, sloping almost imperceptibly from an elevation of 97 m in the northeast, to 67 m A.S.L. in the southwest. The area is drained by two streams, one which has its source in the forest. The parent material is a sandy till, mostly compact with a hard consistence and a massive to pseudo-platy structure. The climate is maritime, with a mean annual precipitation of about 1140 mm.

The soils were classified as dominantly Eluviated Dystric Brunisols on the freely drained sites, as Orthic Eutric Brunisols on the moderately well drained sites, as Gleyed Eutric Brunisols on the imperfectly drained sites, and as Rego Gleysols (Clayton _et al._, 1977) on the poorly drained

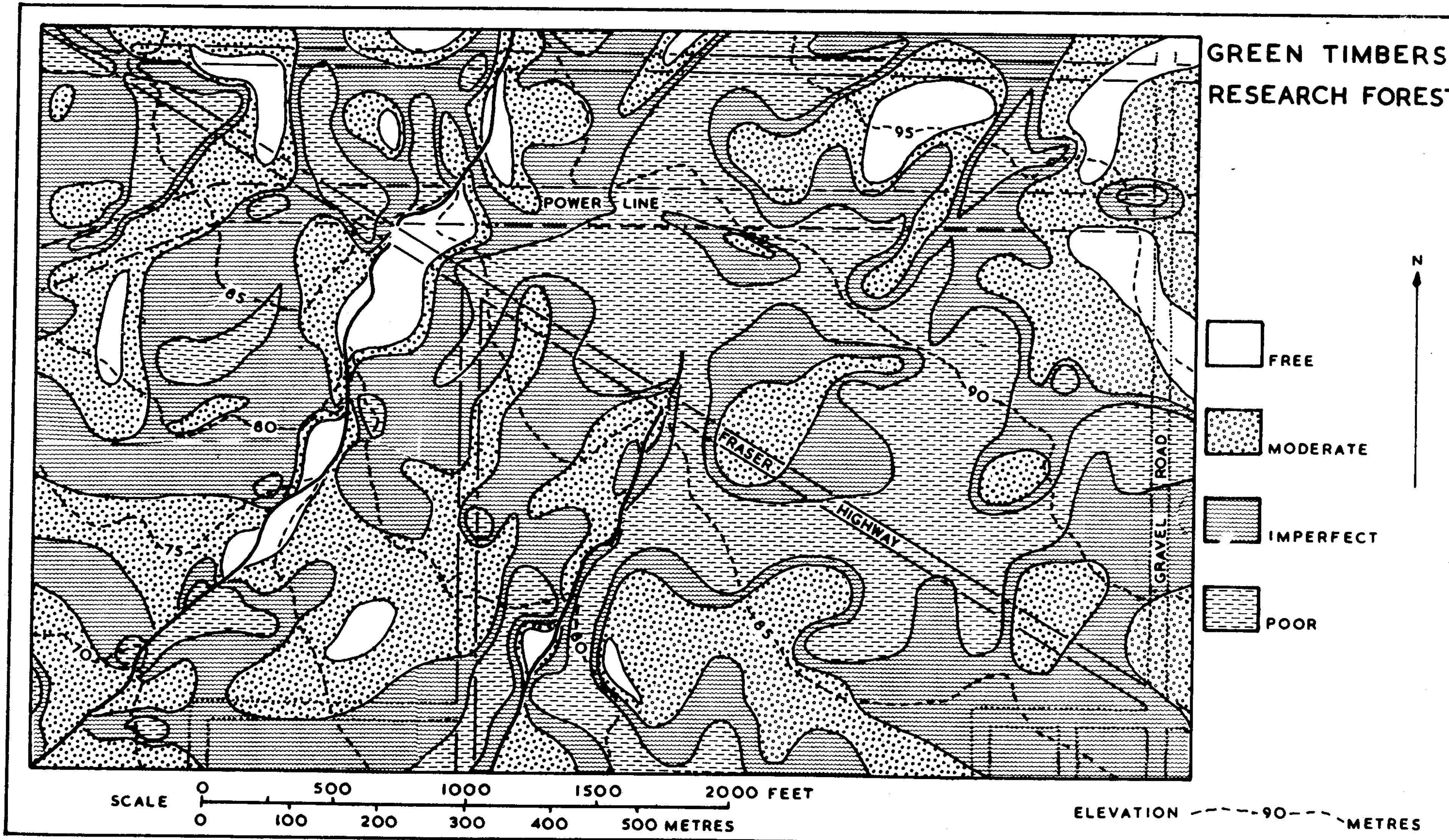


Fig. 7. Map of internal soil drainage based on the field survey.

sites with a variable peaty surface layer up to 30 cm thick. Freely drained soils occupy low ridge crests and slopes scattered across the forest, and some river banks (Fig. 7). Poorly drained soils are most extensive on peaty flats forming the catchment head of one of the streams.

There was a relationship obvious in the field survey between the degree of compaction of the subsoil and internal soil drainage, poorly drained soils occurring where the subsoil is hardest (Compare Figs. 7 and 8). The pressure required for penetration into the parent material (measured with a penetrometer) varied from 1,200 to 2,500 kilopascals, the least pressure being associated with freely drained soils and the greatest pressure with poorly drained soils. In Canada subsoil compaction of this kind is generally associated with pressure from superimposed ice during the last glaciation. The compact, massive or platy-structured subsoils were often associated with a perched water table when the survey was undertaken during May of 1977. In poorly drained soils the B horizon has a texture which varies between sandy to silty clay loam, while in freely drained soils the textures are generally sandy loam. Medium columnar structures are characteristic of the B horizon in poorly drained soils, medium block structures in imperfectly and moderately well drained soils, and granular structures in freely drained soils. Traffic along the power line has compacted the topsoil (Fig. 8), producing pools of surface water after heavy rain, although this pressure appears to have had less effect on subsoil horizons (Fig. 8).

METHOD: PREAMBLE

The systematically distributed data was used as the input for the

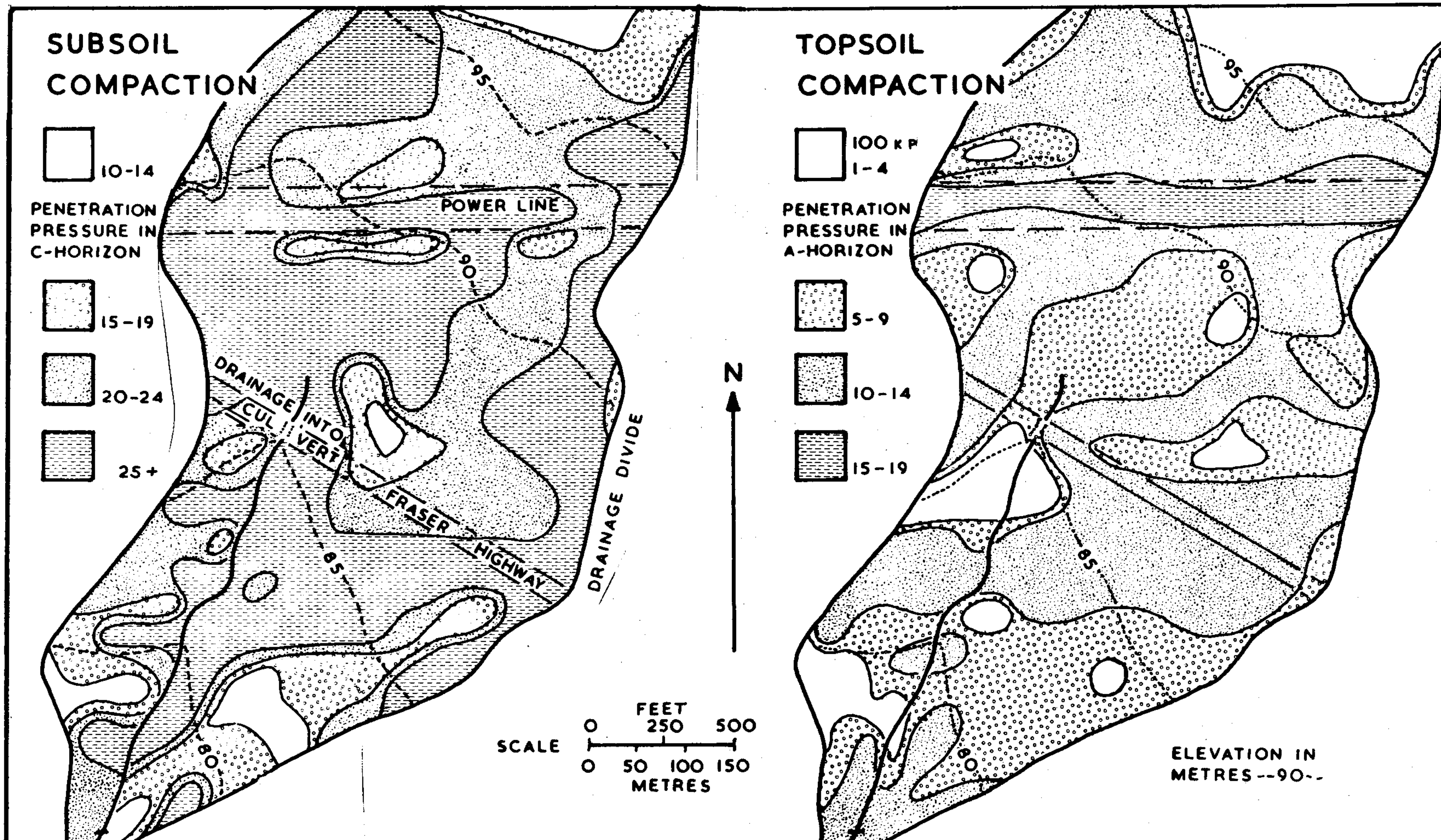


Fig. 8. Soil compaction in the eastern stream catchment.

analyses. In these analyses of synergism the simplest possible case will be considered first, that of finding the most significant pairs of interacting independent variables affecting the spectrum of well drained to poorly drained soils. Next, the most significant groups of three and then four interacting synergists affecting drainage are regressed.

A 20% sample extracted randomly from the original population of 425 sites was kept out of the analysis and was used to help monitor any improvement of predictive accuracy as the number of variables within each synergistic interaction was increased. Thus, there were 340 sites for the analysis and 85 sites for the check.

The analysis consisted of the multiple regression on single variables, and synergistically interacting combinations of two, three and four variables. There were 11 independent variables (texture, structure and compaction of the B and C horizons, the depth of the C horizon, slope, elevation, landform and forest cover-type). Forest cover-type was included since it can influence soils (Hills and Boissoneau, 1960; Crampton, 1970) as much as soils can influence forest cover.

From the original 11 single variables it was possible to create 55 two-variable combinations, 165 three-variable combinations and 330 four-variable combinations, totalling 561. Many of these possible combinations will have little influence on internal soil drainage. Therefore, the calculation of simple correlation coefficients between dependent and independent variables identified a limited number of significant interactions, which were fed into the regression.

## METHOD: ANALYSIS

All the variables were classified into the same arbitrary number of eight categories. The categorization of synergistically interacting variables was accomplished within the program in the following manner. For each significant combination of two independent variables a two-dimensional, 8 x 8 matrix was constructed to embrace all possible combinations of categories for these two variables. Within this matrix the observed internal drainage for each site was recorded in the appropriate cell representing the particular combination of categories characteristic of each site. 340 site observations distributed in an 8 x 8 matrix assured that most cells in the matrix were occupied by at least one observation, although there was a distinct clustering of observations within cells representing particular category combinations.

In each cell, values for the dependent variable were averaged. Cell means were then ranked and divided into eight classes of internal drainage, which allowed the identification of the combinations of categories for the two independent variables involved in the interaction which could be equated with each drainage category. Also, this procedure involved no predetermined assumptions about the relationship between dependent and independent variables. If this reclassification for reducing the large number of category combinations had not been adopted, the program would have been completely unmanageable. It would not have been possible to define a surrogate variable acting for two independent variables, equated with eight classes of internal drainage so that the surrogate could serve as the input into the regression equally with the single variables.

Fig. 9. $r^2$ values associated with multiple regression analyses involving ranked combinations of independent variables, with up to two-, three- or four-variable combinations allowed into the analyses with the single variables.

| | single variables | plus up to two-variable combinations | plus up to three-variable combinations | plus up to four-variable combinations |
|---|---|---|---|---|
| 2 analysis | 0.47 | 0.70 | 0.87 | 0.96 |
| 2 check | 0.39 | 0.53 | 0.67 | 0.78 |
| ariables entified umulative $r^2$) | structure of C (0.26) | depth to C compaction of C (0.39) | elevation depth to C compaction of C (0.61) | forest type elevation depth to C compaction of C (0.85) |
| | depth to C (0.33) | elevation compaction of C (0.50) | slope forest type structure of B (0.77) | elevation texture of C structure of B structure of C (0.94) |
| | compaction of C (0.36) | slope forest type (0.56) | elevation forest type texture of B (0.82) | elevation forest type texture of B texture of C (0.96) |
| | structure of B (0.40) | elevation depth to C (0.61) | elevation texture of C compaction of C (0.85) | |
| | forest cover (0.42) | depth to C structure of B (0.64) | forest type depth to C structure of B (0.87) | |
| | slope (0.44) | forest type compaction of C (0.66) | | |
| | elevation | site type elevation (0.68) | | |
| | compaction of B (0.47) | forest type structure of C (0.70) | | |

For each significant combination of three variables a three-dimensional, 8 x 8 x 8 matrix was constructed to embrace all possible combinations of categories for these three variables. The same procedure was adopted as for two-variable combinations, so that the interaction could be processed in terms of eight categories of internal drainage like single variables. Similarly, an 8 x 8 x 8 x 8 matrix was constructed for each possible four-variable combination, to allow the calculation of a surrogate variable for processing along with single, two-variable and three-variable surrogates.

The analysis ranked and identified the most important variables or their surrogates influencing internal soil drainage, tabulated for single variables, plus two-variable, three-variable and, finally, four-variable surrogates (Fig. 9). The output of the regression was in the form of incremental additions to the intercept for each category combination (Fig. 10). The sum of the increments predicted the internal drainage for a site.

For each two-variable matrix there was an average of 14 cells empty within the total of 64; for each three-variable matrix there was an average of 370 empty cells within the total of 512; for each four-variable matrix there was an average of 3862 empty cells within the total of 4096 cells. As the power of the synergism increased, that is as the number of variables within each interaction increased, and the number of cells in each matrix increased, so the 340 site observations were clustered within an increasingly smaller part of the total analytical matrix. This clustering can be observed in the field in that certain profile attributes are often seen associated together (eg. clay texture and columnar structure), whereas other profile attributes are not normally seen associated together (eg. clay

Fig. 10. Four-variable interactions for the three most important surrogates. Categories defined for the 1st and 2nd interactions. Regression increments and other statistical data listed.

category descriptions or mid-class marks

**1st Interaction**

| drainage increment | depth to C | compaction of C | elevation | forest type |
|---|---|---|---|---|
| 1 = 0.00 | 47-cm | 9-100kp | 76-m | dense conifers |
| free | | | | |
| 2 = +1.16 | 45 | 11 | 84 | open conifers |
| 3 = +2.10 | 43 | 13 | 92 | dense hardwoods |
| moderate | | | | |
| 4 = +3.15 | 41 | 15 | 96 | open hardwoods |
| | | | 100 | |
| 5 = +3.62 | 39 | 17 | 96 | bare grounds |
| imperfect | | | | |
| 6 = +4.48 | 37 | 19 | 88 | scrub |
| 7 = +5.54 | 35 | 21 | 80 | open mixedwoods |
| poor | | | | |
| 8 = +6.62 | 33 | 23 | 72 | dense mixedwoods |

$r^2 = 0.85$

**2nd Interaction**

| drainage increment | elevation | texture of C | structure of B | structure of C |
|---|---|---|---|---|
| 1 = 0.00 | 100-m | sand | loose | loose |
| free | | | | |
| 2 = +1.12 | 96 | sandy loam | granular | granular |
| 3 = +2.11 | 92 | loam | fine blocky | fine blocky |
| moderate | | | | |
| 4 = +2.78 | 88 | silt (loam) | coarse blocky | coarse blocky |
| 5 = +3.68 | 84 | silty clay loam | columnar | columnar |
| imperfect | | | | |
| 6 = +4.53 | 80 | clay loam | fine platy | fine platy |
| 7 = +4.98 | 76 | sandy clay loam | coarse platy | coarse platy |
| poor | | | | |
| 8 = +6.14 | 72 | clay loam/organic | massive | massive |

**3rd Interaction** elevation forest type texture of B texture of C

drainage increment: 1 = 0.00 2 = +0.16 3 = +0.86 4 = 1.76 5 = +2.20 6 = +2.71 7 = +3.90 8 = +4.00

intercept = -.674 mean = 4.92 $r^2 = 0.96$ standard deviation = 2.02

texture and loose structure).

Using the random sample as an independent population, the check was accomplished by identifying the appropriate cell mean in the analytical matrix, and regressing the drainage predicted by the corresponding output increments with the field determined drainage.

RESULTS

When single variables, and two-, three- and four-variable surrogates were allowed into the analysis simultaneously, the correlation between each single or surrogate independent variable and internal soil drainage was most significant for the greatest variable combination, in the final analysis for four-variable surrogates (Fig. 9). The $r^2$ values for the analysis, and check, reflected the much greater analytical power achieved by increasing the number of variables within each synergistic interaction. Additionally, only three four-variable surrogates explained about 96% of the variation. By comparison, five three-variable surrogates were needed to achieve lesser $r^2$ values in the check and analysis, and 11 two-variable surrogates (Fig. 9).

If the $r^2$ value for an interacting surrogate was related to the loss of $r^2$ produced when each of the interacting variables was dropped from a combination in turn, then the relative importance of the individual variables within the interaction could be assessed. As the number of variables involved within synergistic interactions was increased, and the regression $r^2$ values increased, so the interpreted contribution (in terms of $r^2$ value) of each variable within the interaction became more equal. Thus, within a four-variable interaction, withdrawal of any one of the variables produced an approximate 25% loss in $r^2$ value. Some independent variables were found to influence internal soil drainage only when interacting with other independent variables; for example, the texture of the B and C horizons (Fig. 9).

The synergism for the most important four-variable surrogates affecting internal drainage is listed in Fig. 10. Within the most important interaction, free drainage is associated with deep soils having poorly compacted subsoils, at low to medium elevations under coniferous forest, whereas poor drainage is associated with shallow profiles having strongly compacted subsoils, also at low to medium elevations, under mixedwoods. It is the moderately and imperfectly drained soils that tend to occur at higher elevations, in moderately deep profiles with moderately compacted subsoils, beneath mature and immature hardwoods, respectively. Most of the variation is explained by this synergistic interaction (analysis $r^2$ is 0.85, Figs. 9 and 10). Additional accuracy may be achieved in the prediction of internal soil drainage by using the second and third most important four-variable interactions which define less common synergism.

The cell means within a two-variable interaction matrix can be plotted on a two-dimensional graph and the distribution pattern contoured (Fig. 11). One class of internal soil drainage may be associated with a particular category of each variable. For example, poor internal drainage is associated with great compaction of the C horizon at shallow depth (Fig. 11a). Poor drainage may also be associated with a continuous change of each variable, for example, with slight compaction at low elevations, grading into great compaction at relatively moderate to high elevations

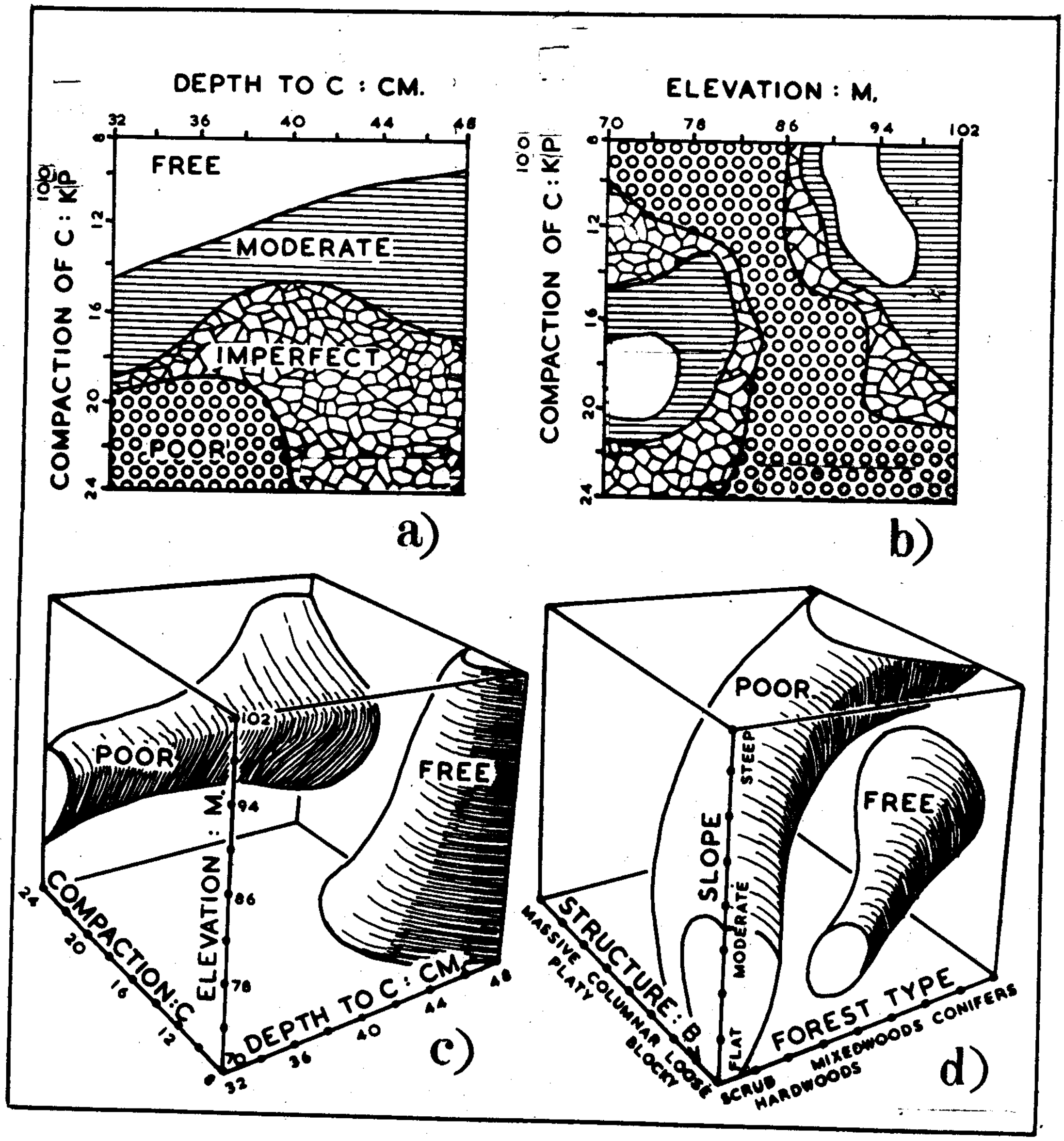


Fig. 11. Upper two-variable interaction diagrams; a) poor drainage is associated with a strongly compacted, shallow soil profile, whereas free drainage is associated with slight compaction through a range of soil profile depths including, particularly, shallow depths; b) poor drainage is associated with a balanced increase in elevation and degree of compaction of the subsoil, whereas free drainage is associated with either a strongly compacted subsoil at low elevations, or a slightly compacted subsoil at high elevations. Lower three-variable interaction diagrmas; c) poor drainage is associated with a strongly compacted subsoil through a range of profile depths, but chiefly at middle elevations, whereas free drainage is associated with slightly compacted subsoils in deeper soil profiles through a range of elevations; d) poor drainage is associated with a more or less balanced increase in the size of structural units in the B horizon, an increase in steepness of slope and an increasing coniferous content in the forest, while free drainage is associated with mixedwood to coniferous forest, moderate slopes and loose, granular or blocky structures in the B horizon.

(Fig. 11b). One class of internal drainage may be associated with two apparently different environments, which is the ecological concept of the bimodal distribution. Thus, free drainage is associated with slight compaction at high elevations, or with great compaction at relatively low elevations (Fig. 11b).

When cell means within a three-variable interaction matrix are plotted on a three-dimensional graph (Fig. 11c and d), the observations are more dispersed and bimodal distributions are difficult to discern. To produce the most important three-variable interaction, the additional variable (elevation) added to the most important two-variable interaction involving the depth of the C horizon and its compaction, gave rise to a substantial change in the drainage distribution (compare Fig. 11a and c). Similarly, a four-variable interaction cannot be predicted from the behaviour of its components, whether singly or in combinations of less than four. Unfortunately, it is not possible to graph the cell means within a four-variable interaction. However, it is speculated that the bimodal distributions are apparent in two- and three-variable matrices primarily because certain important synergists have been omitted from the interaction.

## SUMMARY

As the number of independent variables within synergistic combinations was increased, up to a total of four, so the correlation with the dependent variable, internal soil drainage, became more significant, and predictions of drainage based on the analysis became increasingly more effective. These predictions were checked with an independent population.

Thus, the importance of synergism within a natural landscape was fully demonstrated.

Field experience in the study-area clearly revealed the relationship between the degree of compaction of the subsoil and the state of internal drainage, but left other relationships ill-defined. The analysis contributed the additional information that the depth to the C horizon, the elevation and forest cover type were also important influences on internal soil drainage when interacting synergistically. Although the influence of texture and structure on internal drainage would be suspected from general field experience, this influence was defined for the study-area only by the analysis. However, for these relationships to be understood requires field experience.

## REFERENCES


Bender, W.H. 1971. Soils and septic tanks. Agric. Info. Bull. 349, Soil Cons. Serv., U.S. Dept. Agric.

Clayton, J.S., Ehrlich, W.A., Cann, D.B., Day, J.H. and Marshall, I.B. 1977. Soils of Canada. Can. Dept. of Agric., Research Branch, Ottawa.

Crampton, C.B. 1970. Some effects of conifers on poor soils in the Atlantic Maritime Region. Advancing Frontiers of Plant Sciences, 25: 199-211.

Geiger, R. 1973. The Climate near the Ground. Harvard University Press, Cambridge, Mass.

Goodman, L.S. and Gilman, A. 1970. The Pharmacological Basis of Therapeutics. The Macmillan Company, London and Toronto. p. 25.

Grable, A.R. 1971. Effects of compaction on content and transmission of air in soils. Monograph; Compaction of Agricultural Soils, Am. Soc. of Agric. Engin., pp. 154-164.

Gumbel, E.J. 1954. Statistical theory of extreme values and some practical applications. National Bureau of Standards, Washington, D.C., Applied Mathematics, Series 33.

Harris, W.L. 1971. The soil compaction process. Monograph; Compaction of Agricultural Soils, Am. Soc. of Agric. Engin., pp. 9-44.

Hills, G.A. and Boissoneau, A.N. 1960. Physiographic descriptions and basic principles required for planning multiple land use in the Glackmeyer Development Area. In the Glackmeyer Report of Multiple Land-Use Planning, Ontario Department of Lands and Forests.

Krajina, V.J. 1969. Ecology of forest trees in British Columbia. University of British Columbia, Ecology of west North America, 2, pp. 1-146.

Oke, T.R. 1978. Boundary Layer Climates. J. Wiley and Sons, New York.

Roddick, J.A. 1965. Vancouver North, Coquitlam and Pitt Lake Map-areas, British Columbia. Geological Survey of Canada, Department of Mines and Technical Surveys, Ottawa, Mem. 335.

Saini, G.R. and Hughes, D.A. 1972. Soil compaction reduces potato yields. Canada Agriculture, 17, 28-29.

Sporns, U. 1963. Frequency and severity of storms in the Lower Fraser Valley, B.C. Canada Department of Transport, Meteorological Branch, Cir.-3848, Tec.-469.

Trouse, A.C. Jr. 1971. Effects of soil temperature on plant activities. Monograph; Compaction of Agricultural Soils, Am. Soc. of Agric. Engin., pp. 269-276.

Willis, W.O. and Raney, W.A. 1971. Effects on compaction on content and transmission of heat in soils. Monograph; Compaction of Agricultural Soils, Am. Soc. Agric. Engin., pp. 165-177.

Wilkinson, C.F. 1976. Insecticide Biochemistry and Physiology. Plenum Press, New York and London. pp. 631-635.

Wright, J.B. 1966. Precipitation patterns over Vancouver City and Lower Fraser Valley. Canada Department of Transport, Meteorological Branch, Cir.-4474, Tec.-623.