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Part II Soil Drainage Studies

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1. Introduction

A collaborative research project between the Soil and Plant Processes Division, Manaaki Whenua-Landcare Research and the New Zealand Forest Research Institute commenced in 1990 for the Department of Conservation, West Coast Conservancy, to investigate techniques for re-establishing indigenous vegetation on an open-cast coal mine site at Giles Creek, Westland. A rehabilitation trial was established at Giles Creek Mine to evaluate site preparation methods and the performance of various indigenous tree and shrub species. The investigation of soil drainage conditions covered in this report began in 1992 and was commissioned by the Science and Research Directorate of the Department of Conservation.

2. Background

Alluvial gold mining and open-cast coal mining are industries important to the Westland economy. Many of these mining activities are on lands administered by the Department of Conservation, which are commonly in indigenous forest ecosystems but sometimes in grazing leases. In the past, after mining of indigenous forest ecosystems, there has been little planned or managed restoration. Abandoned mining sites have often reverted to gorse, manuka and other scrub vegetation, which in some places has eventually developed into a secondary forest after many decades.

This report is concerned with work done as part of the collaborative research project to investigate techniques for re-establishing indigenous vegetation on an open-cast coal-mine site at Giles Creek, Westland. The trial area was divided into plots for evaluation of site preparation treatments in which three soil and gravel media were placed onto either compacted or ripped underlying gravels. Details of the soil resources present before mining, the trial design, and earthworks are given in Ross & Mew (1993). The New Zealand Forest Research Institute (NZFRI) are investigating the performance of 12 indigenous tree and shrub species on the trial plots. Previous work by NZFRI in a pilot trial of plant establishment had indicated that survival and growth were influenced by the soil moisture regime of the planted sites, with poor drainage as the main contributing factor to poor survival. The measurements to characterise soil drainage in the trial plots commenced one month after the NZFRI had completed planting the 12 tree and shrub species and continued over 18 months. In addition, brief investigations using the techniques that had been tested at Giles Creek were made at 4 other sites with known rehabilitation histories.

3. Objectives

- To conduct strategic sampling of soil/gravel moisture conditions just after planting (October) and under dry (February) and wet (May) climatic periods to evaluate waterlogging and drought as factors determining plant survival during the establishment phase (1992/93).
- To conduct measurements in wet conditions in late winter-spring (August-October 1993) and dry conditions in late summer (February 1994) to determine whether the differences in soil drainage and root zone aeration that were detected in the first year after establishment of the Giles Creek mined land rehabilitation trial persisted in the second year.
- To select, in consultation with DoC West Coast Conservancy, sites with known histories of successful or failed vegetation establishment after mining, and conduct short-term measurements using the techniques tested at Giles Creek.
- Prepare a report (by June 1994) on the results of the field measurements and soil physical aspects of root zone manipulation on restored mined land

4. Sites and Methods

4.1 SOIL WATER AT THE GILES CREEK TRIAL SITE

The trial site

Full details of the design of the rehabilitation trial at Giles Creek Mine are given in Ross & Mew (1993). The soil water measurements commenced in October 1992 shortly after NZFRI had planted the trial plots with 12 indigenous species. Fig. 1 (based on Fig. 4 of Ross & Mew 1993) shows the field lay-out of the trial.

The trial contained three plant-growth media:

1. **Original soil profile placed over gravels,** i.e., mixed organic layers and mineral topsoil on subsoil on gravels (here identified as the SH replacement treatment).
2. **Mixed soil placed over gravels,** i.e., all organic and mineral soil materials mixed together on gravels (here identified as the MS replacement treatment).
3. **Gravels to the surface,** i.e., no soil material (here identified as the GO replacement treatment).

Half of the soil placement (SH and MS) and GO plots contained compacted gravels (NR treatment), the other half of the plots had the underlying or surface gravels ripped to about 0.8 m depth at 1.5 m spacings (R treatment). The soil materials were dug with an hydraulic excavator and the organic plus topsoil material was segregated from subsoil. Soil materials were transported in dump-trucks or scrapers. Subsoil was spread on the trial plots directly from scrapers, but the topsoil plus organic material was spread with an hydraulic excavator without tracking across the deposited material at any time.

Bare-rooted and container-grown nursery stock of 12 indigenous tree and shrub species were planted in rows at 1×1 m spacing by NZFRI in September 1992. There were two replicate blocks of plants in each of the 6 plots.

Tensiometer measurements

Three sites for soil-water measurements were selected by row numbers along traverse lines in each of the 6 plots. This gave a systematic lay-out of sampling locations in each plot but a random selection of species at those locations. At each location in the SH and MS plots two tensiometers were installed on 6 October 1992 with their porous ceramic cups at depths of 25 and 50 cm. Tensiometers were installed on 8 October in the GO plots at 25 cm depth only. Details of the location of tensiometers are given in Table 1. A hand auger was used to install the tensiometers, adding a slurry of silt to improve contact between the tensiometer cup and the soil. The tensiometers remained in place throughout the measurement period (October 1992 to March 1994).

The tensiometers used consisted of a porous ceramic cup, 5 cm long, attached to a length of plastic tubing closed off at the top with a rubber septum stopper. The tensiometers were filled with de-aired water, leaving a 1 cm air gap below the septum stopper. The air pressure at the upper end of the tubing was measured by inserting a syringe needle attached to a pressure transducer through the septum (Marthaler *et al.* 1983). A Loktronic™ tensiometer monitor, mbar model, was used to measure the pressure, which was displayed on the digital readout as a negative number that is the difference between atmospheric pressure and the pressure below the septum. The readings with the Loktronic monitor are in mbar, but results are presented in cm of water pressure units to simplify the comparisons of soil water potentials and depths in the soil. As most measurements were in very wet conditions, when the soil matric potential was less negative than -50 cm of water, the time required for re-equilibration after insertion of the needle was usually less than 1 minute.

The soil matric potential (or soil water tension) in the soil at the level of the middle of the ceramic cup was obtained by adding the length of the water column in the tensiometer stem to the reading on the Loktronic monitor. Results are presented as means for the sets of 3 tensiometers at each depth in each plot.

Hydraulic (or total) potentials were calculated with reference to the local ground surface at the tensiometer sites, and hydraulic potential gradients were calculated where measurements were made at two depths in the soil on the SH and MS replacement plots. Hydraulic potential gradients indicate whether water is moving upwards or downwards in the soil (there may also be a lateral component to water movement, but that was not investigated).

FIG. 1 LAY-OUT OF THE PLOTS IN THE GILES CREEK BEECH FOREST REHABILITATION TRIAL, SHOWING THE LOCATION OF TENSIOMETERS. TRIAL LAYOUT FEBRUARY 1992.
(BASED ON FIG. 4 OF ROSS & MEW 1993).

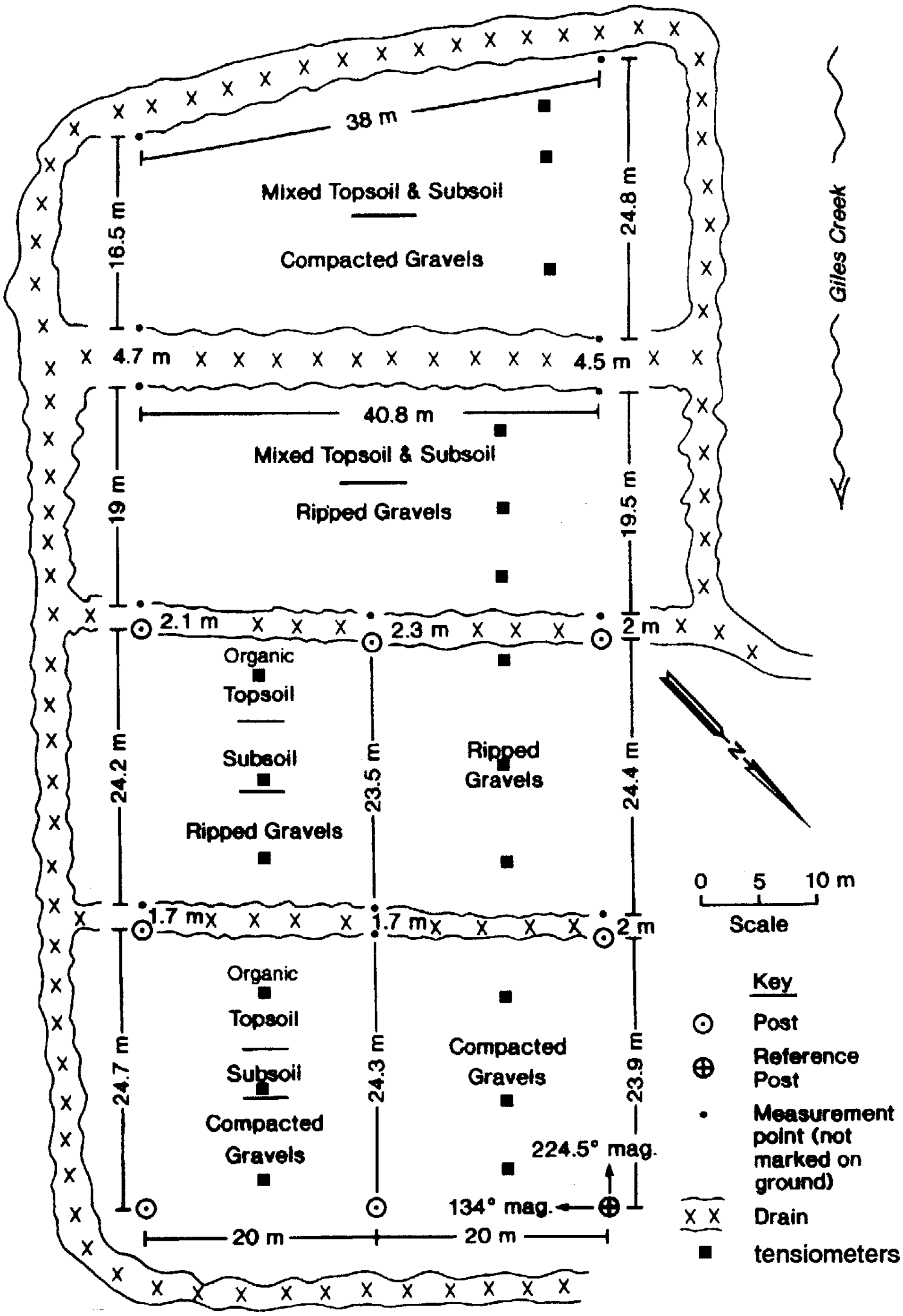


TABLE 1: LOCATION OF TENSIOMETERS

SITE CODE	MATERIAL	TREATMENT	REPLICATE	(GROUP) SPECIES	STOCK TYPE	PLANT NUMBER IN BLOCK
SHNR1	SH	non-rip	2	(11) *Nothofagus fusca*	bare-rooted	5–7
SHNR2	SH	non-rip	2	(3) *Hebe salicifolia*	bare-rooted	3–6
SHNR3	SH	non-rip	1	(10) *Nothofagus solandri*	container	5–7
SHR1	SH	rip	2	(10) *Aristotelia serrata*	container	8–11
SHR2	SH	rip	2	(1) *Nothofagus solandri*	container	10–12
SHR3	SH	rip	1	(8A) *Hebe salicifolia*	container	10–12
MSNR1	MS	non-rip	2	(6) *Dacrycarpus dacrydiodes*	container	6–8
MSNR2	MS	non-rip	1	(12) *Coprosma robusta*	bare-rooted	9–11
MSNR3	MS	non-rip	1	(1) *Podocarpus totara*	bare-rooted	8–10
MSR1	MS	rip	2	(8) *Nothofagus fusca*	bare-rooted	8–10
MSR2	MS	rip	1	(16) *Nothofagus fusca*	container	5–7
MSR3	MS	rip	1	(5) *Coprosma robusta*	bare-rooted	6–8
GONR1	GO	non-rip	2	(11) *Coprosma robusta*	bare-rooted	5–6
GONR2	GO	non-rip	2	(2) *Fuchsia excorticata*	container	8–9
GONR3	GO	non-rip	1	(10) *Nothofagus solandri*	bare-rooted	9–10
GOR1	GO	rip	2	(9) *Dacrycarpus dacrydiodes*	bare-rooted	10–11
GOR2	GO	rip	1	(18) *Hebe salicifolia*	container	8–9
GOR3	GO	rip	1	(8) *Aristotelia serrata*	container	4–5

SH = Original soil profile placed over gravels

MS = Mixed soil placed over gravels

GO = Gravels to the surface

Replicate refers to the 2 replicates of 12 plant species in each plot

4.2 SOIL AERATION AT THE GILES CREEK TRIAL SITE

In the SH and MS replacement plots, soil oxygen diffusion rate (ODR) was measured using platinum micro-electrodes with a Jensen Model D meter. A voltage of 650 mV relative to the Ag/AgCl electrode was used and an equilibration time of at least 3 minutes was allowed after the voltage was applied. On 4 occasions, clusters of 4 electrodes were installed at 4 cm depth around two or more seedlings at randomly selected points on the SH and MS plots. Additional measurements were made on the overburden mudstone/ sandstone and the GO plots. The meter readings of current flowing to the micro-electrodes (in µamperes) was converted to oxygen diffusion rate (µg cm^{-2} min^{-1}) using the factor supplied by the manufacturer.

4.3 WATER BALANCE AND DROUGHT STRESS AT THE GILES CREEK TRIAL SITE

Failure of planted seedlings on rehabilitated sites may arise from either waterlogging and poor aeration, or from drought stress where root development is inadequate to supply water to meet evaporation demand. Dry periods are relatively infrequent in the West Coast environment, but periods of low rainfall can persist for 3-4 weeks in late summer. In such periods evaporation can become important in drying the soil sufficiently to affect plant survival and growth, and it was therefore important to obtain soil water data in these infrequent dry periods. To provide a guide for timing tensiometer measurements under dry conditions, a daily water balance model was used with rainfall data retrieved by radio-telemetry from the Landcare Research catchment research area at Maimai (Rowe *et al*. 1994). The model allowed the development of soil drying to be estimated without visiting the field site until a substantial soil water depletion had developed. Commencing at a time when the soil had been fully re-wetted, the model calculated the accumulating amount of water lost from the soil as the difference between daily rainfall and evaporation (here referred to as the potential soil water depletion, PSWD, in mm water). On average, the rainfall at Giles Creek greatly exceeds the evaporation, so that usually after a week or two the soil water storage is fully recharged again (PSWD returns to zero) and a water surplus occurs which is lost from the site as runoff or drainage.

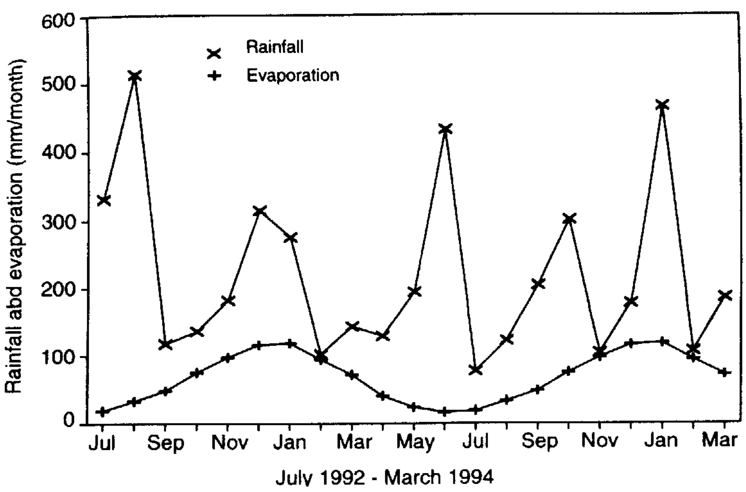
Rainfall data came from a tipping bucket raingauge at Maimai catchment M13. Rowe *et al.* (1994) have shown that annual rainfall decreases by 75 mm per km as distance from the Paparoa Range increases, so mean annual rainfalls are expected to be about 300 mm lower at M13 than at the Giles Creek site. The effect of the rainfall gradient will be to give greater water surplus at Giles Creek than at Maimai during wet periods, but there is not expected to be much difference during dry periods. The evaporation estimates were taken from published values calculated by the Penman method, averaging the Hokitika and Westport data to give an estimate for the Giles Creek site (New Zealand Meteorological Service 1986). The Penman values are judged to be appropriate for the low-stature vegetation at the trial site, except when drying of the soil surface continues long enough to restrict evaporation from bare ground amongst the plants. However, such periods are rare and evaporation at the Penman potential rate has been assumed throughout.

4.4 ADDITIONAL SITES

The tensiometer and oxygen diffusion rate measurement techniques described above were used for short-term studies at other restored sites. Suitable sites were identified in consultation with DoC staff in Hokitika in May 1994. Tensiometers and platinum u-electrodes were installed and left overnight to equilibrate before readings were taken. In addition, measurements of some other soil properties were made at these sites. Infiltration rate was obtained from steady-state rates of water entry into the soil in 73 mm diameter stainless steel rings pushed 30 mm into the ground. Soil bulk density, volumetric water content, and air-filled pore space were obtained with 50 mm long, 73 mm diameter core samples. Details of these sites are given together with the results in Section 6.4. Oxygen diffusion rate was also measured in November 1993 at the demonstration trial on mudstone/sandstone overburden at the Giles Creek mine (described in Ross & Mew 1993, p.16).

5. Results

FIG. 2 MONTHLY RAINFALL MEASURED AT MAIMAI DURING THE STUDY PERIOD, JULY 1992-MARCH 1994 (UPPER LINE), AND AVERAGE OF MONTHLY EVAPORATION ESTIMATES FOR WESTPORT AND HOKITIKA BY PENMAN METHOD (LOWER LINE)



The soil water and aeration monitoring on the Giles Creek site aimed to determine the role of waterlogging and drought in relation to plant performance in the trial. Weather conditions during the investigation were expected to have an important influence on the monitoring programme. The balance of evaporation and rainfall largely determines the occurrence of soil water surplus or depletion, and hence the opportunity to monitor extremes of wet or dry soil conditions (see section 5.3). Figure 2 shows the monthly rainfall (measured at Maimai catchment research area) compared with the longterm average Penman evaporation. No month had less rainfall than evaporation, and many months had a water surplus greater than 100 mm. Short periods of soil drying did occur, but are not revealed by the monthly data.

The calculations with the daily soil water balance model show there were a few short periods when the cumulative evaporation depleted soil water storage by more than 20 mm of water, especially in November 1992 and February 1994 (Fig. 3). Over the full 18-month period there were 69 days with calculated soil water depletion (PSWD, mm) greater than -20 mm, and 9 days with PSWD greater than -40 mm. The tensiometer readings were made on several dates with a range of PSWD values from very wet conditions during rainfall (PSWD = 0 mm) to the driest day (18 February 1994) in the 18-month period (PSWD -58 mm, Fig. 3). The full set of tensiometer data is given in Table 2, and is discussed in relation to soil drainage (section 5.1) and drought stress (section 5.3). Soil aeration measurements were made less often than tensiometer measurements and are presented in section 5.2.

FIG. 3 DAILY WATER BALANCE CALCULATED FOR THE GILES CREEK SITE USING RAINFALL DATA FROM MAIMAI AND AVERAGE DAILY EVAPORATION (PENMAN ESTIMATE).
A water surplus occurs on a day when the soil is fully recharged by rainfall; the surplus drains away on that day. Potential soil water depletion (PSWD) occurs when daily evaporation exceeds rainfall, and accumulates until rainfall is sufficient to fully recharge the soil storage.

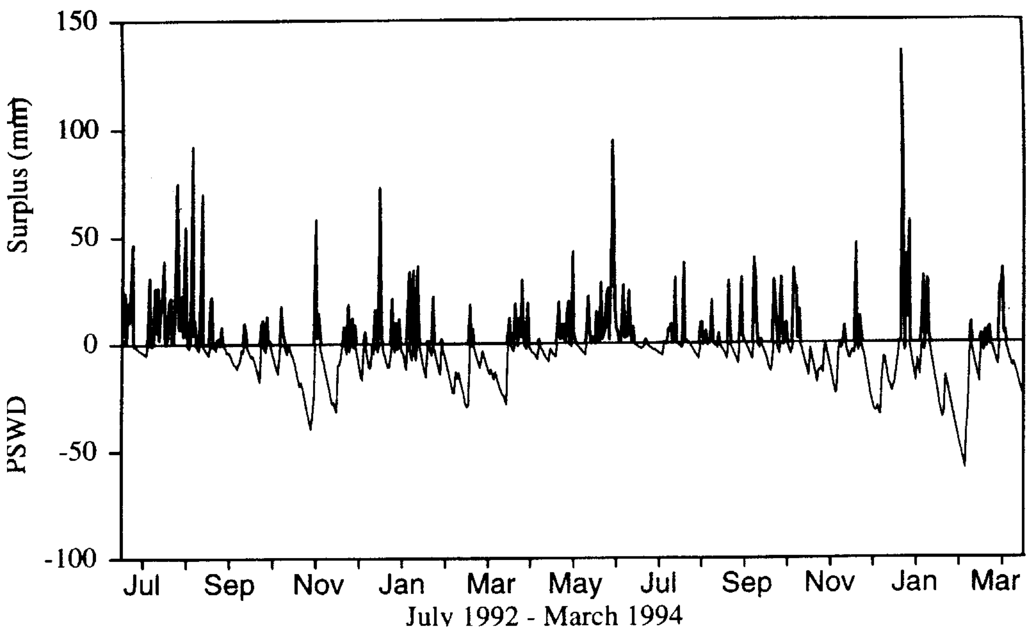


TABLE 2 MATRIC POTENTIALS (cm OF WATER PRESSURE) DERIVED FROM TENSIOMETER MEASUREMENTS AT GILES CREEK MINE RESTORATION TRIAL. VALUES GIVEN ARE MEANS OF 3 TENSIOMETERS AT 25 OR 50 cm DEPTH IN EACH PLOT. REPLACED MATERIALS (SOIL HORIZONS OR MIXED SOIL) OVERLIE GRAVELS WHICH ARE EITHER RIPPED OR NOT-RIPPED. FOR EACH DATE OF MEASUREMENT THE POTENTIAL SOIL WATER DEPLETION (PSWD) CALCULATED FROM DAILY WATER BALANCE (SEE FIG. 3) IS ALSO GIVEN. N/D DENOTES DATA WERE NOT RECORDED.

				SOIL HORIZON REPLACEMENT				MIXED SOIL REPLACEMENT				GRAVEL ONLY	
			PSWD	NON-RIP		RIPPED		NON-RIP		RIPPED		NON-RIP	RIPPED
D	M	Y	mm	25 cm	50 cm	25 cm	50 cm	25 cm	50 cm	25 cm	50 cm	25 cm	25 cm
6	10	92	-15	N/D	-9	-25	-12	-20	3	-38	14	N/D	N/D
7	10	92	-18	-11	-11	-27	-17	-87	-13	-52	3	N/D	N/D
8	10	92	0	1	21	-6	9	16	32	10	32	N/D	N/D
8	10	92	0	5	27	3	21	21	36	17	38	N/D	N/D
9	10	92	0	2	13	-5	13	13	38	11	34	-6	-4
9	10	92	0	2	12	-6	12	15	40	8	35	-5	-6
10	10	92	-2	1	7	-9	5	10	39	4	34	-8	-9
12	10	92	0	10	9	-5	11	15	49	7	38	1	-1
15	10	92	-5	2	6	-8	5	-5	30	-7	24	-27	-34
16	10	92	-8	7	6	-11	-4	-17	21	-15	22	-33	-39
29	3	93	-22	-36	-13	-77	38	-26	17	-65	-49		
29	3	93	-22	-9	-3	-25	0	9	12	-20	14	-17	14
16	4	93	-3	1	1	-8	3	-6	24	2	29	-21	-14
15	6	93	0	2	-1	-4	12	13	37	14	33	0	-2
16	6	93	0	4	1	4	16	20	39	18	35	-1	8
17	6	93	0	3	1	5	12	18	35	13	32	-4	0
9	11	93	-11	-1	3	-9	7	7	28	7	32	-2	-5
15	12	93	-27	-15	-22	-26	-20	-55	9	-35	11	-62	-73
18	2	94	-58	-48	-29	-129	-54	-311	-79	-150	-25	-573	-516
10	3	94	-3	-11	-11	-16	-2	-15	16	-9	25	-27	-25

5.1 SOIL DRAINAGE AT THE GILES CREEK TRIAL SITE

October 1992

The tensiometers were installed in the SH and MS replacement plots on 6 October 1992 to assess soil drainage in the plots shortly after planting was completed in September. Onset of heavy rainfall soon after the installation was completed provided an opportunity to characterise the dynamic drainage behaviour of the 3 types of material and the interaction between the nature of the material and the ripping treatment. Tensiometer measurements were taken from 6 to 16 October 1992 during and after this large rainfall event - initially 2-3 times per day and then at 1-2 day intervals. The data on 6 October were rejected because they indicated that the tensiometers had not reached equilibrium in the short time between installation and the readings. Tensiometers were installed in the GO plots on 8 October, so no data were available for the GO plots before this rainfall event.

FIG. 4 CALCULATED DAILY WATER SURPLUS AND DEPLETION (PSWD) (MM) DURING OCTOBER 1992.

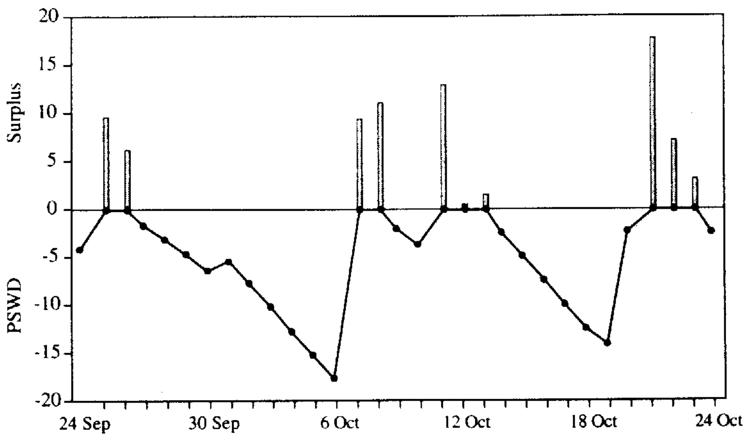
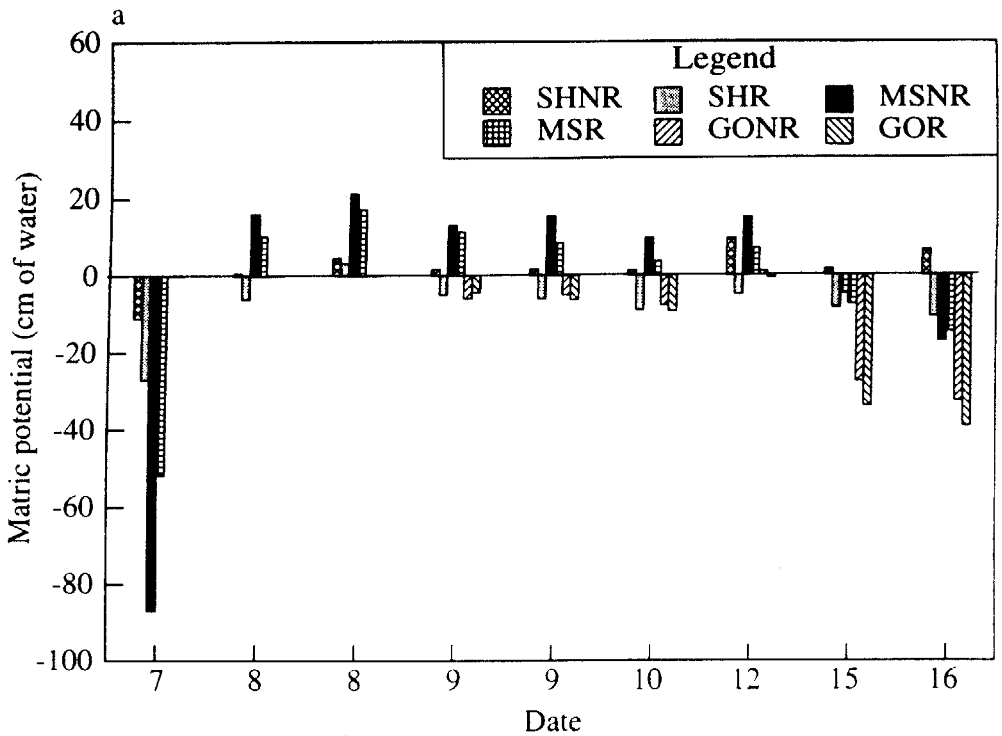
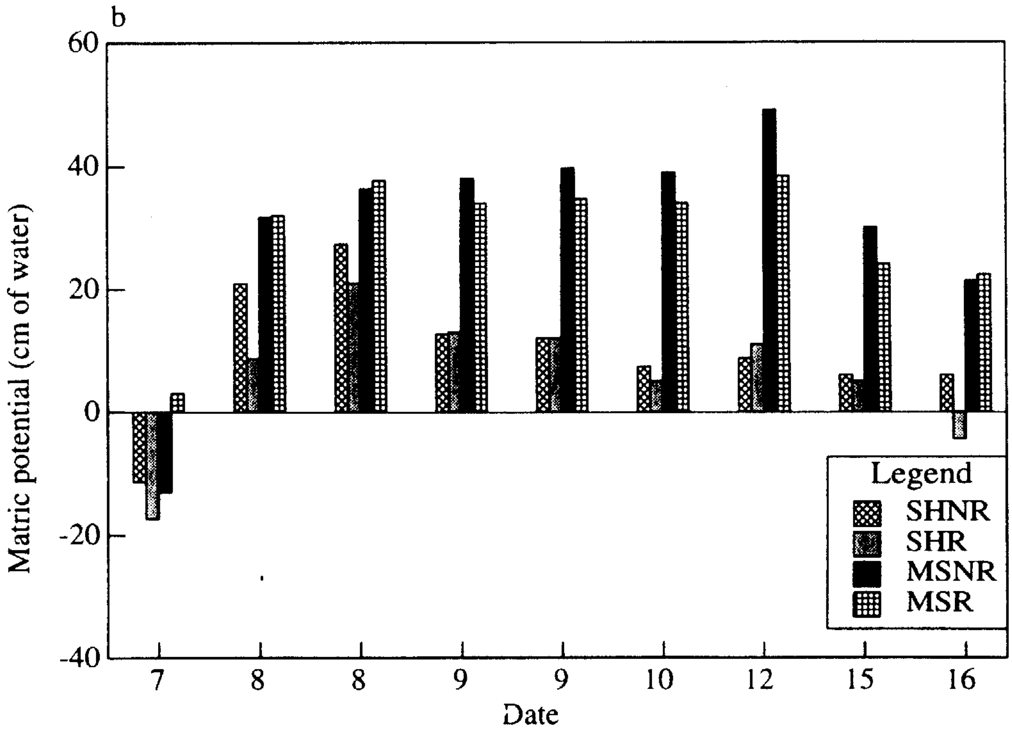


Figure 4 shows the calculated water balance in October 1992. A period of several days without rainfall gave cumulative soil drying to reach a potential soil water depletion (PSWD) of -18 mm on 6 October. Rainfall on 7 and 8 October was sufficient to fully re-wet the soil and produce a surplus to drain through the soil. Further rainfall on 11 October was followed by a drying period that continued until 19 October.

The tensiometer data show how the soil water responded to this weather sequence (Figs. 5 and 6). As expected from the lack of rainfall in the previous week (Fig. 4), the soil was relatively dry when instruments were installed on 6 October. The first soil water matric potentials were negative (i.e. measurements were above the water table) except at the 50 cm depth in the MS replacement plot over ripped gravels (Fig. 5). Matric potentials at 25 cm depth became positive in both the SH and MS replacement plots on 8 October and again on 12 October, indicating the water table everywhere was between the soil surface and the 25 cm depth. Under the wettest conditions, during rainfall on the afternoon of 8 October, matric potentials in the MS plots were +20 cm of water at 25 cm depth, indicating the water table was then only 5 cm below the ground surface. Visual observations at that time showed extensive surface water on the MS plots but not on the SH plots. Matric potentials at 50 cm depth rose during rainfall on 7-8 October, remained above zero for several days, and were substantially higher in the MS plots than in the SH plots.

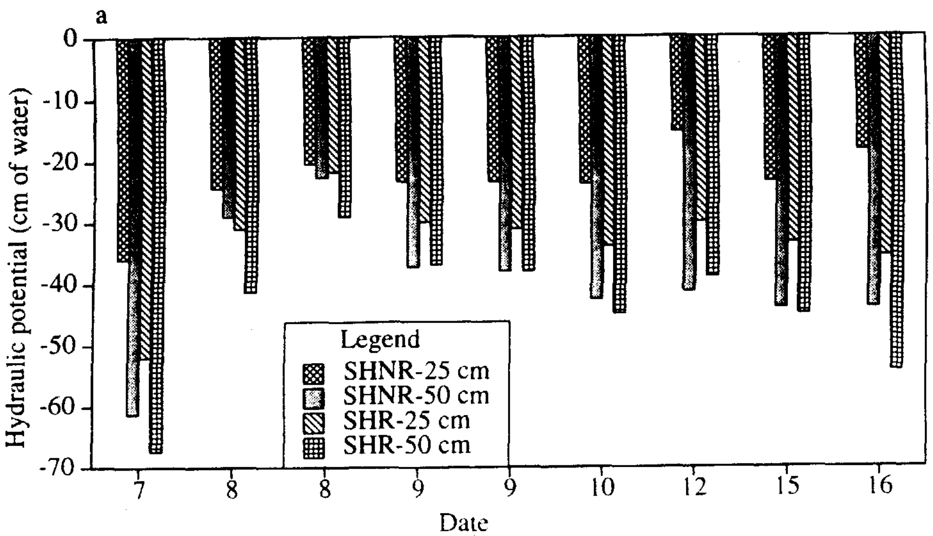
FIG. 5 SOIL WATER MATRIC POTENTIALS AT 25 CM (A) AND 50 CM (B) DEPTHS IN THE SH, MS, AND GO PLOTS DURING THE WEATHER SEQUENCE IN OCTOBER 1992 SHOWN IN FIG. 4.

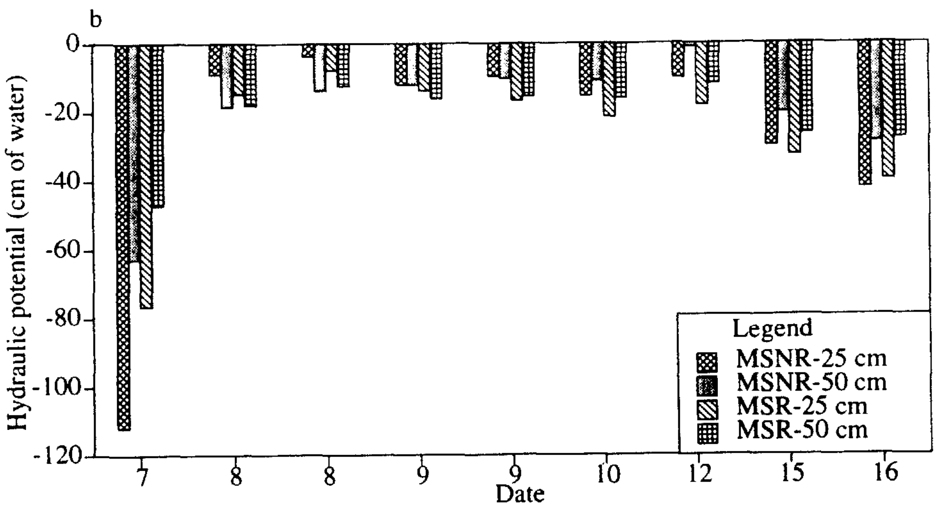




The hydraulic potentials show an important difference between the MS and SH plots (Fig. 6a,b). On 7 October, before the rainfall, the hydraulic potential in the SH plots was more negative at 50 cm than at 25 cm depth, indicating the gradient is downwards and water was draining down through the soil. This pattern persisted through the rainfall and at all observations up to 16 October. In contrast, the hydraulic gradient was upwards in the MS plots on 7 October (indicating water moving upwards to evaporate at the surface), but the gradient was downwards during and after rainfall on 8-9 October, and then became upwards again. The limited data at 25 cm in the GO plots show they resembled the SH during rainfall, but matric potentials rapidly became more negative as the soil dried by 16 October.

FIG. 6 SOIL WATER HYDRAULIC POTENTIALS (A) IN THE SOIL HORIZON (SH) REPLACEMENT PLOTS AND (B) IN THE MIXED SOIL (MS) REPLACEMENT PLOTS DURING THE WEATHER SEQUENCE IN OCTOBER 1992 SHOWN IN FIG. 4.





Overall, the tensiometer data during this wet period show while rain was falling the SH plots had the water table deeper than the MS plots. Continued drainage after rainfall allowed the water table to fall to 50 cm within a few days in the SH plots, but it remained closer to the surface in the MS plots and was losing water upwards to evaporation.

Effects of ripping

Compared with the differences between materials shown in Figures 5 and 6, the effect of ripping is very small. In all plots the matric potentials tend to be a little lower in ripped than in non-ripped plots. The upwards gradient in the MS material indicates that evaporation is more important than drainage irrespective of whether or not ripping was done. Thus the properties of the material in the 0 - 50 cm depth are of greater importance than ripping below 50 cm. The effects of ripping were quantified in two ways:

- visual observations of water levels;
- closer examination of the tensiometer data during and soon after rainfall.

1. Water in holes at time of planting

Records kept at the time of planting on the MS replacement plots showed that water was present in 5.8 % of the holes (total number of trees planted was 450) on the Ripped plots and 17.8 % of the Non-ripped plots (M. Davis, pers. comm.).

2. Surface ponding

Surface ponding in the Ripped and Non-ripped plots on the MS treatment during rainfall on 8 October was quantified by walking along the three rows containing the tensiometers and counting how many of the plants were surrounded by water in those rows and the two adjacent rows (a total sample of 180 plants). Surface water surrounded 5.0% of the plants on the ripped plots and 22.7% on the non-ripped plots. There was no surface ponding on the SH plots at this time. Tensiometers had not been installed in the GO plots at this time and ponding was not surveyed.

3. Tensiometer data

If it is assumed that there is approximate equilibrium in the upper 25 cm of soil, the matric potential derived from the tensiometers at 25 cm depth is related to depth of water below the ground surface by:

Depth to water = 25 - Matric potential at 25 cm

Thus a matric potential equal to zero indicates the water level is at 25 cm depth. Table 3 summarises derived depths to water on 8-10 October.

TABLE 3 DEPTH TO WATER TABLE FROM GROUND SURFACE DERIVED FROM TENSIOMETERS AT 25 cm DEPTH DURING AND AFTER RAINFALL ON 8 OCTOBER.

TREATMENT	DEPTH TO WATER TABLE (cm)			
Day (October 1992) Time	8 1530	9 1000	9 1500	10 1200
SH Rip	22	30	31	34
SH Non-rip	20	23	23	24
MS Rip	8	14	17	22
MS Non-rip	4	12	10	15
G Rip	N/D	29	31	34
G Non-rip	N/D	31	30	33

Surface ponding may arise either because intake is limited by soil structure at the surface (e.g., capping developed under raindrop impact), or because the water table intersects the low-points of the ground surface. The tensiometer data on the afternoon of 8 October were taken shortly after the survey of surface ponding was completed. In the MS plots the water is inferred from tensiometers to be 8 cm below ground in the Ripped plots and 4 cm below ground in Non-ripped plots. Given the uneven ground surface in the plots, it seems likely that the observed greater extent of surface ponding on the Non-ripped MS plots reflects more frequent intersection of the ground surface by the higher water table rather than a surface-capping mechanism.

Overall, the three sets of observations consistently indicated less water close to the ground surface in the ripped plots. The rainfall history before the observations in the planting holes on 4 September was similar to that before 10 October, when water tables were at 22 cm depth in the Ripped MS plot and 15 cm in the Non-ripped MS plots. Thus in both the MS and SH materials the ripped plots have water tables 2 - 10 cm lower than on non-ripped plots on the day of rainfall and for a few days after rain. The data on hydraulic potentials (Fig. 6) indicate that this difference persisted until 16 October in the SH plots but not in the MS plots. This is expected since the hydraulic gradients indicate that by this date the water loss from the MS plots was driven by evaporation rather than by drainage. Some caution is needed in actually attributing the difference between ripped and non-ripped plots to the ripping of the underlying gravels: small differences in elevation, or proximity to surface drains may also play a role in determining the position of the water table relative to the local ground surface.

Ponding of water has been noted on the gravels at times, including on 12 October (J.J. Payne, pers. ZAcomm.). On this occasion the tensiometer data indicate the water table was 25 cm below the ground surface, which suggests that restricted intake, because of surface conditions among the stones and boulders, is the reason for ponding. Some redistribution and packing of the fine-textured matrix may be involved, but more investigation is needed to define the conditions leading to temporary ponding on apparently "porous" gravels.

Other measurements under wet conditions

June 1993 was very wet, with 325 mm of rainfall between 1 and 16 June. Tensiometer measurements made on 15-17 June 1993, and gave almost identical results to those obtained under similar weather conditions on 7-10 October 1992 (Table 2). Similarly, the data on 10 March 1994 were taken a few days after rainfall that had re-wet the soil, and closely resemble the 15 October 1992 results. Frequency analysis of the water balance data shows that in the 18 months studied about one-third of the days had a water surplus, when conditions are expected to be similar to those on 8-10 October and 15-17 June with a water table within 10 cm of the ground surface on the MS plots.

5.2 SOIL AERATION AT THE GILES CREEK TRIAL SITE

Results of measurements of oxygen diffusion rates (ODR) are given in Table 4. The main comparisons were made in the SH and MS plots, in October 1992, June and November 1993, and March 1994. Two conclusions are drawn from these results:

- The SH plots consistently have higher oxygen diffusion rates than the MS plots.
- There are no consistent differences between the ripped and non-ripped plots.

There is no information on the oxygen diffusion rates that restrict root or whole-plant growth for the range of species used in the Giles Creek trial. The mean values on all dates for the MS plots are a little above the level of 0.075 $\mu g\ cm^{-2}\ min^{-1}$ that Gradwell (1967) found adequate for seedling ryegrass plants, although many of the individual measurements on the MS plots were below that level. Most mean values on the MS plots are below the critical ODR value of 0.2 $\mu g\ cm^{-2}\ min^{-1}$ cited for many agricultural plants (McIntyre 1970), but nearly all mean values for the SH plots are above this critical value. Comparisons made between groups of 4 electrodes placed close to live and dead plants of beech and manuka showed no consistent differences. Variation was greater between dates for the SH plots than for the MS plots, but the variation had no obvious explanation, e.g., the large difference amongst the results in the SH plots when measurements were made under wet conditions in October 1992 and June 1993.

TABLE 4 OXYGEN DIFFUSION RATES IN THE SH AND MS PLOTS. THE MEAN, STANDARD DEVIATION, AND NUMBER OF MEASUREMENTS ARE GIVEN FOR EACH PLOT ON EACH DATE. UNITS ARE μg cm^{-2} min^{-1}.

	SH						MS					
	NON-RIPPED			RIPPED			NON-RIPPED			RIPPED		
DATE	MEAN	SD	N	MEAN	SD	N	MEAN	SD	N	MEAN	SD	N
9/10/92	0.63	0.08	8	0.63	0.18	8	0.17	0.07	16	0.17	0.05	16
16/6/93	0.19	0.08	9	0.26	0.09	9	0.14	0.04	9	0.12	0.06	9
17/6/93	0.35	0.09	10	0.55	0.19	9	0.16	0.07	10	0.18	0.08	10
9/11/93	0.28	0.12	18	0.28	0.09	18	0.10	0.05	24	0.17	0.08	24
10/3/94	0.39	0.19	9	0.36	0.17	11	0.21	0.15	12	0.15	0.09	12

Two other materials were also tested with the ODR equipment: the gravel-only (GO) plots, and the overburden in the demonstration trial at Giles Creek. Surprisingly, the results on the GO plots in March 1994 were very low (mean 0.11 μg cm^{-2} min^{-1} in both the ripped and non-ripped plots). These ODR measurements were made a few days after rainfall, when the tensiometers showed that the matric potential was -25 cm of water which should have been sufficiently low for large pore spaces amongst the gravel to be drained and full of air. Measurements on the mudstone and sandstone overburden under wet conditions on 12 November 1993 and again a few days after rainfall in March 1994 gave mean values of 0.35 μg cm^{-2} min^{-1}, well above those from the MS plots, although both materials appear to be dominated by poorly-structured fine-textured material. ODR results are discussed further in relation to the measurements made at other sites in May 1994 (section 5.4).

5.3 DROUGHT STRESS AT THE GILES CREEK TRIAL SITE

The data on PSWD in Table 2 show that the matric potential at 25 cm depth in the MS and GO plots became negative quite rapidly when soil water depletion reached 10 mm. The hydraulic gradient in the MS plots is then upwards, indicating water loss by evaporation rather than by drainage; more severe drying closer to the surface is expected. Frequency analysis of the water-balance data showed that soil-water depletion exceeded 10 mm on 12% of the days in the 18 months studied. The most prolonged drying occurred in February 1994 (Fig. 3) and the matric potentials at this time are given in Table 2. The severity of near-surface drying is greatest in the GO plots, where matric potentials were lower than -500 cm of water at 25 cm depth, which approaches the value when uptake of water by plants can be restricted. Thus, in spite of the high frequency of rainfall at this site, the short periods of drying that occur in many summers produce conditions that make drought a possible cause of poor establishment on replaced gravels while roots are confined to a shallow zone.

The data for the MS plot also show that soil water potentials were falling rapidly as the soil water was depleted. Because the frequently high water table in this material may limit deep rooting, plants could soon be under stress under conditions like those in February 1994. More information is needed on the conditions during dry periods between the ground surface and the 25 cm depth in this material.

Soil water potentials showed less change during the dry period in the SH plots than in the other treatments. The high available water storage in the O and Ah horizons under forest (e.g., Jackson 1984, Table 2) is the probable reason for good water availability after replacement of these materials.

The maximum calculated PSWD shows that the driest soil conditions in 1992-93 occurred early in the summer in November when PSWD reached 40 mm, but measurements were not made at that time. The planned programme of measurements (see objectives) was based on the expected occurrence of driest conditions in the late summer (Jan-Mar) but it was not particularly dry then.

5.4 ADDITIONAL SITES

There are various options for replacement of land after mining to meet different goals for future management of the site. McQueen (1982) gave definitions of three terms widely used in this field:

Restoration: recreating the original topography and re-establishing the previous land use.

Rehabilitation: creating conditions for a new, planned and substantially different use of the mine site.

Reclamation: restoring a derelict site to some use with approximately the original vegetation cover.

These terms have not been used consistently in practice in New Zealand. In the present context it is important only to distinguish between situations where the goal is to return the land to its original state and other situations where the opportunity is taken to create conditions that are designed for effective use of the land for a specified purpose.

On 2-6 May 1994, measurements were made at four sites near Hokitika:

- Kennedy Creek
- Striplands Creek
- Mikonui
- Greenstone

These are all sites that had been mined for gold and then restored. The Kennedy Creek site is a former grazing lease that was rehabilitated to pasture, whereas the other three sites were restored with the aim of returning them to indigenous forest.

Heavy rain fell on 2-3 May, but no further rain fell on 4-6 May while the measurements were made at these sites.

Kennedy Creek

This site was mining licence 32-2544 at grid reference J33 528256. Hokitika soils were present before mining to 6 m depth in 1987-88. Topsoil recovery was considered adequate when the site was restored in October 1988 with fertilizer and lime applications before sowing a grass mix. The grazing licensee is of the opinion that a good standard of rehabilitation was achieved.

The site was visited first on 2 May, during rainfall, and was seen to be very wet with surface water on much of the site. Rushes were common and had recently been mown. Tensiometers (2 replicates) and ODR probes (10 replicates) were installed on 3 May during rainfall. Tensiometer and ODR readings, infiltration measurements, and soil core sampling were done on 4 May, about 12-24 hours after rainfall ceased.

Three areas within a paddock were investigated, designated Upper, Middle, and Lower areas. The paddock had a fairly uniform slope with a fall of about 1 m in the 100 m distance from the Upper to the Lower site. The Upper area was on the highest ground, where grass cover was noticeably better than everywhere else in the paddock, rushes were less abundant and surface water was absent. The Middle and Lower areas were typical of the paddock as a whole with rushes abundant and surface water present. Results of the measurements are given in Table 5.

TABLE 5 PHYSICAL PROPERTIES OF TOPSOIL AT KENNEDY CREEK SITE RESTORED TO PASTURE

	UNITS	UPPER	MIDDLE	LOWER
Matric Potential	cm water			
15 cm		-7.5	15	12.5
30 cm		1.5	22	27
ODR	$\mu g\ cm^{-2} min^{-1}$	0.054	0.048	0.040
Dry Bulk Density N/D	t/m^3		1.47	1.36
Total Porosity	% vol.	43	47	N/D
Water Content	% vol.	37	40	N/D
Air-filled pores	% vol.	7	7	N/D
Infiltration rate	mm/h	64	12	N/D

N/D indicates not measured at this site.

The tensiometers showed soil water potentials at the Upper area corresponding to a water table more than 20 cm below the ground surface, but those at the Middle and Lower areas indicate the water table was close to the soil surface. The ODR rates are low at all sites, as is the air-filled porosity. The bulk density at 1.4 t/m^3 is not unusual for pasture topsoil on the West Coast, and lies in the range 1.0 - 1.7 measured for A horizons of Hokitika soils *in situ* (C. Ross, pers. comm.).

Infiltration rates were high on the Upper site, but those on the Middle site would at times be exceeded by rainfall rates and result in overland flow. Because slopes are long, uniform, and gentle (*c.* 1°) water accumulates down the slope and maintains wet surface conditions. Introducing more relief on such sites at the time of soil placement is the simplest means of creating a higher proportion of sites with the better soil physical characteristic measured at the Upper site in this paddock. In its present condition, ploughing channels across the slope, linked to an outlet, would break the slope into shorter segments and provide an opportunity for conditions to improve on at least the upper part of each segment.

Francis & Morton (1991) investigated the effect of gravel mole draining on physical properties and pasture production on an imperfectly drained recent soil (Harihari silt loam) near Hokitika. They found that although mole draining modified properties of the subsoil it had no effect on the topsoil; slow topsoil infiltration rate (15-30 mm/day) was the main cause of the poor drainage status of the soil, and air-filled porosity (6-9 % by volume) was below the value of 10% sometimes taken as the minimum level for unimpeded exchange of soil air with the atmosphere. They concluded that moling could not be justified and that improved drainage required either an increased infiltration rate at the surface or a system to create more relief and increase surface flow during rainfall. The topsoil bulk density at the site used by Francis & Morton (1991) was 1.0 -1.1 t/m^3 which is much lower than at the Kennedy Creek site; soil surface pugging was a problem at their site and it seems likely that firmness of the surface at Kennedy Creek is probably an asset in terms of the ability to carry stock in wet periods. Overall the results of Francis & Morton (1991) reinforce the conclusion that the main requirement is greater surface relief; mining actually provides an opportunity to undertake rehabilitation to meet this need rather than simply restoration of the original surface form with little relief.

Striplands Creek

This site was mining licence 32-2356 at grid reference J33 503266. Soils were not identified before mining, but Flagstaff and Turiwhate soils occur nearby. The site was mined to 5 m depth in 1987, with minimal topsoil recovery. It was restored in 1988 with replaced soil being concentrated at the eastern end. Regeneration studies were carried out on 4 plots, two in areas with adequate topsoil either planted with native seedlings (area 1) or spread with woody slash (area 2), one on minimal topsoil which was neither planted nor spread with slash (area 3), and one on a former access track (area 4). Gorse is now common on this site, although some planted and many naturally regenerated seedlings are present. On May 3, during rainfall, tensiometers and ODR electrodes were installed on three sites, one representative of each of the areas 1, 2, and 3 used in regeneration studies, but not in the access track. Water was present in nearly all tensiometer holes at the time of installation. The ODR electrodes were placed in two groups of 5 around native tree seedlings about 2 m apart, and the tensiometers (2 at 15 and 30 cm depths) were placed along a line between those seedlings. Readings were taken on 4 May, about 18 hours after rain ceased.

TABLE 6 TENSIOMETER AND ODR RESULTS AT STRIPLANDS CREEK.

	UNITS	AREA 1 PLANTED	AREA 2 SLASH	AREA 3 MINIMAL SOIL
Matric potential				
15 cm	cm water	-15	-8	-3
30 cm		-5.5	-8	14.5
ODR	$\mu g\ cm^{-2} min^{-1}$	0.13	0.08	0.10
Living plant*	%	42	36	13

(D. Eastwood, pers. comm.)*

The results indicate that at the time of measurement the water table ranged from 30 cm below ground at area 1 to 15 cm below ground surface at area 3, and oxygen diffusion rates were low. The depth to groundwater follows the same trend as the observed living plant score on sample plots.

Mikonui

This site was mining licence 32-1213 and 32-2109 at grid reference I33 286076. Harihari soils were mapped for the site before mining to *c.* 6 m depth in 1990 (Ross & Mew 1981). The site was restored in 1991 with subsoil and some tree debris spread on the surface. A small number of native plants were planted in winter 1992, but recruitment of plants by natural regeneration is considered good. There is very little gorse on this site. The site is on ground that is *c.* 10 m higher than its surroundings and gently rolling. There were some signs of sheet and minor rill erosion on bare areas. Vegetation is noticeably clumped, apparently often on patches *c.* 2-5 m across that have tree debris and/or forest floor material present. Tensiometers and ODR electrodes were installed on 4 May on 5 areas: a steep bare slope at the edge of the site with only lichen ground cover (site 1); largely bare ground (sites 2 and 3); and vegetation clumps (sites 4 and 5). The tensiometer (2 replicates) and ODR (10 replicates) readings were taken on 5 May, together with infiltration rates (4 replicates). Results are given in Table 7.

TABLE 7 PHYSICAL PROPERTIES OF TOPSOILS AT THE MIKONUI SITE

VEGETATION	UNIT	SITE				
		1 LICHEN	2 80% BARE	3 50% BARE	4 WINEBERRY	5 TUTU
Matric potential 15 cm 30 cm	cm water	 -7.5 -2	 -59 -59	 -45 -51	 -16 -28	 -40 -36
ODR	ìg cm^{-2}min^{-1}	0.24	0.18	0.29	0.24	0.26
Infiltration rate	mm/h	115	150	N/D	830	N/D*

** N/D not determined*

Tensiometer results show the sloping site has the lowest infiltration rate (but still high enough for almost all rainfall to infiltrate), and the water table at 22 - 32 cm below the surface. The lowest matric potentials were at the bare ground sites, suggesting these are the best drained. Overall the data indicate good drainage, adequate oxygen, and high infiltration rates, and it may be soil chemical or biological factors rather than physical ones that influence vegetation distribution at this site.

Sediment pond traps have been used at this site, and future management of these causes some concern. Tensiometer and ODR measurements were made in the silty deposit, among rushes and sedges. The tensiometers indicated water potentials in equilibrium with the water table at the ground surface showing the material was saturated throughout, and oxygen diffusion rates were very low (mean 0.8 µamps -convert). A soil auger was easily pushed to 1.2 m, and showed that while the upper 10-20 cm were moderately firm the material below was very soft.

Difficulties in rehabilitation of similar mine slurry materials have been reported in Australian gold-mining sites. In their analysis of the restoration of tailings from sandy alluvium, Emerson *et al.* (1992) noted that in fine textured tailings by the time a volume sufficient to give good aeration has drained (10% of soil volume) the penetration resistance is too high (greater than 2.5 MPa) for root penetration. They deduced that none of the water present was available for plant growth. At Mikonui, because the high rainfall will prevent structural improvement by drying, these sediment pond sites are unlikely to support anything other than wetland plants and may be hazards. Spreading the material thinly amongst coarse-texture overburden may be the best treatment.

Greenstone

This site was mining licence 32-2998 at grid reference J32 693395. Maimai or similar soils were present before mining to 4-5 m depth in 1992. The site was restored in 1993, with up to 1 m of topsoil mixed with tree debris spread on the land surface. It is intended that this site should be left to naturally regenerate to native forest. As yet the site is not fenced and has been grazed by sheep. Some natural regeneration was seen, but cover is poor. A remnant of the original mixed hardwood-podocarp has been left near the mined land. The natural soil profile in the forest remnant was inspected by auger; they comprised 20 cm of dark reddish-brown humic silt loam (H), 10-15 cm of light brownish-grey silt loam (Ah/Ahg), on gravels at 35-40 cm. Water was present at 35-40 cm. The profile at site 2 contained a pale grey silt subsoil layer, a few cm thick, over a thin iron pan at 30 cm. The surface of the restored material is uneven, consisting of flat-topped high areas between deep ruts formed by machinery tracking during soil spreading. Measurements were made in the forest remnant (2 sites), and on high and low areas in the restored land. Tensiometers (2 replicates) and ODR electrodes (10 replicates) were installed on 5 May and measurements with these were made on 6 May (2-3 days after rainfall). In addition, infiltration measurements were made and soil core samples were taken on 6 May.

TABLE 8 PHYSICAL PROPERTIES OF TOPSOILS AT THE GREENSTONE SITE

	UNIT	SITE				
		1 FOREST	2 FOREST	3 HIGH	4 HIGH	5 LOW
Matric potential 15 cm 30 cm	cm water	 -15 -5	 -24 -20	 -14 -1	 -14 -5	 +4 +7
ODR	ìg cm^{-2}min^{-1}	0.30	0.55	0.10	0.07	0.14
Dry Bulk Density	(t/m^3)	N/D		1.10		0.93
Total Porosity	(%vol.)	N/D		58		64
Water Content	(% vol.)	N/D		25		37
Air-filled pores	(% vol.)	N/D		32		27
Infiltration rate	(mm/h)	60		1440		1300

The results of measurements at this site provide an opportunity to compare conditions on restored land and in natural forest. Soil physical characteristics of Maimai and other poorly drained soils were reported by Jackson (1984), and these demonstrated the importance of the H and Ah horizons for plants as they have abundant readily-available water to meet transpiration needs and they are the only part of the soil profile that has sufficient air space to be well-aerated for much of the year. The bulk density of the soil in the top 10 cm of the restored site is about 1.0, which is similar to natural Ah horizons reported by Jackson (1984). The tensiometers indicated a water table at 30-40 cm in the natural forest stand, about 30 cm below ground on the high part of the restored site and 10 cm below ground in the depressions. Soil water contents were also higher in the depressions. However, the material in the depressions has the same very high infiltration rates, high air-filled pore space, and similar bulk densities to the material on the high ground. Thus the soil in the depressions had not been compacted by machinery, but apparently simply displaced to be closer to the water table. The infiltration rate in the forest stand is similar to saturated hydraulic conductivities measured on Ah horizons elsewhere (Jackson 1984). Air-filled pore space would be expected to be about 15-20 % of soil volume, somewhat less than was measured in the replaced soil. Surprisingly, the ODR results are low in the restored soil in spite of the large air-filled pore space; the reason for this is not known, although it could arise from a low wetted surface area of the electrodes.

6. Conclusions

The measurements made during this investigation have shown that selection of the material to be the future surface layer for plants to grow in is clearly the best way to obtain good establishment and growth of the desired vegetation on sites after mining.

- The Mixed Soil replacement at Giles Creek stays nearly saturated with water and Field layout of the trialdeficient in oxygen for long periods after rainfall, providing an environment that limits revegetation with native shrub and tree species and allows the site to become dominated by rushes.
- The Kennedy Creek site, the sediment pond at Mikonui, and to a slightly lesser extent the Striplands site, all have drainage and aeration limitations similar to the Mixed Soil treatment at Giles Creek for revegetation to native species or, at Kennedy Creek, to pasture .
- The Soil Horizon replacement in the Giles Creek trial has provided an upper horizon that is not water-logged or poorly aerated, so that physical conditions are not limiting revegetation. Similar physical conditions have been created at the Greenstone site.
- Development of high soil water tensions on the Giles Creek Gravel Only plots during long periods with low rainfall indicate a drought limitation for plant establishment on this material.
- The observations at Giles Creek and at Greenstone were made in the first year or two after soil replacement. Although these initial measurements show some replacement techniques can create desirable soil physical conditions when soil is replaced, there is a need to follow up with further assessments at approximately 3-year intervals until the success of revegetation is assured.

Mechanical working of the material during and after replacement may be a means of reducing the adverse properties of the surface materials.

- At Giles Creek, ripping the underlying gravels had only a small effect on soil water potential and none on oxygen diffusion rate. This result is similar to the observation of Francis & Morton (1991) that sub-surface drainage by moling had little benefit for improving drainage and pasture production on imperfectly drained soils in Westland.

- Surface contouring, e.g., by hump and hollow formations, to increase surface flow during periods of high rainfall and provide elevated sites for trees at a greater height above the water table, are the more likely to succeed in getting good establishment. This approach is similar in effect, but on a smaller scale, to that used in plantation forestry on West Coast pakihi wetland (Jackson 1987).
- If the local relief is increased there is inevitably an increased risk of soil erosion, as has happened to some extent at the Mikonui site. Rapid establishment of ground cover is an obvious solution, either by spreading forest or scrub slash or by oversowing.

We used two main techniques for monitoring soil conditions at Giles Creek, tensiometers for soil drainage and ODR for soil aeration. These methods, and additional measurements of infiltration and physical characteristics of core samples, were used in the brief investigation of other sites.

- Tensiometers have been a valuable technique in all studies. They have provided clear evidence of the drainage behaviour of the three materials in the plots at Giles Creek, and demonstrated the lack of response to the ripping treatment. They also demonstrated the differing soil drying behaviours and susceptibility to drought of the three materials during periods without rainfall.
- Tensiometers also provided useful information on drainage in the brief studies at the four additional sites. They are recommended as the most appropriate technique for soil water studies on mined sites in the West Coast climatic regime; they should be installed at two (or more) depths so that hydraulic gradients can be determined.
- The platinum electrode ODR technique was used to assess soil aeration in the plots at Giles Creek, showing that the low oxygen supply in the Mixed Soil replacement plot is the main cause of poor plant survival. Similarly, the ODR data indicate the low oxygen status at the Kennedy Creek pasture site.
- Usually, high ODR values reliably indicate good aeration, as in the Soil Horizon replacement treatment at Giles Creek. There were some unexpectedly low ODR values at Greenstone and in the Gravel Only plots at Giles Creek when other evidence indicated these soils were very well aerated; a low wetted area of the electrode is the probable reason for these results. Alternative, more complex procedures for ODR measurements may be needed in such cases (Phene 1986).
- Core sampling and determination of air-filled porosity is a simple alternative method to assess aeration; it is not appropriate in soils with a high content of large stones or coarse woody debris, or in trials where repeated destructive sampling is not acceptable.

7. Recommendations

- Topsoil resources should be protected and used as the new surface horizon when mining sites on the Conservation estate are to be restored to their original vegetation or rehabilitated for use as pastoral leases.
- The land surface formed after mining should have surface contouring to assist shedding of surplus water; erosion control measures may be needed, but rapid development of ground cover is preferable.
- Tensiometers are the most appropriate technique for soil water studies on mined sites in the West Coast climatic regime; they should be installed at two (or more) depths so that hydraulic gradients can be determined.
- The platinum electrode ODR technique can be used to assess soil aeration differences between materials and between methods of soil management.
- Core sampling and determination of air-filled porosity is a simple alternative method that can be used to assess aeration; it is not appropriate in soils with a high content of large stones or coarse woody debris, or in trials where repeated destructive sampling is not acceptable.
- The measurements of drainage and aeration conditions at Giles Creek and at Greenstone should be to followed up at approximately 3-year intervals until the success of revegetation is assured.

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