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WATER YIELD OF LOW-ALPINE SNOW TUSSOCK GRASSLAND IN CENTRAL OTAGO

A. F. Mark* and Jennifer Rowley*†

ABSTRACT

Transpiration and interception studies have confirmed earlier claims that the increased water surplus under large snow tussocks results from their substantial gains by interception. This more than compensates for their relatively high transpiration.

With water potentially the most valuable product of many high mountain areas and the water-deficient Taieri catchment in particular, the conclusion that the maximum water yield (and control) from the low-alpine snow tussock grasslands is obtained (in this region at least) from a natural undisturbed cover warrants testing on a larger scale.

Fifteen non-weighing lysimeters somewhat smaller than a unit area of a single snow tussock, operated for six years in low-alpine snow tussock grassland at *c.* 1000 m on Rock and Pillar Range, have shown that the type and condition of plant cover can appreciably modify the water yield. Untreated snow tussocks provided the greatest water surplus: 63 percent of the 1348 mm mean annual raingauge catch, while a sward of blue tussock yielded significantly less (49 percent). Snow tussocks which initially were either burned or severely clipped were associated with intermediate yields: 60 percent and 54 percent, respectively, for the six-year period, although annual throughput from the burned plants showed a significant increase with time, relative to that of the normal tussocks, coinciding with their recovery. Water surplus under bare soil (56 percent) was also intermediate between normal snow tussocks and the blue tussock sward.

INTRODUCTION

A study begun in 1966 to determine the water balance of narrow-leaved snow tussock grassland under varying management conditions at *c.* 1000 m on Rock and Pillar Range, Central Otago (Mark and Rowley, 1969; Rowley, 1970), was continued, as initially described, for six years. Results for the first two years

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* Botany Department, University of Otago, Dunedin (Miss E. L. Hellaby Indigenous Grasslands Research Fellows).

† Present address: Science Information Division, Department of Scientific and Industrial Research, Wellington.

(Mark and Rowley, 1969) indicated that normal (untreated) snow tussocks (Fig. 1) produce a greater water yield than either a sward of blue tussock or snow tussocks which had been recently defoliated by either clipping or burning.

Preliminary measurements of transpiration and of interception gains by variously treated snow tussocks indicated that the increased water yield associated with undamaged snow tussocks is due not to reduced transpiration but to substantial gains by interception.

The present paper discusses results of the full six-year study as well as some additional aspects that were initiated following the two earlier papers.

METHODS

The procedures described in the two earlier papers were followed throughout the six-year period (October 1966 to September 1972). Soil moisture measurements with gypsum blocks both within the lysimeters and outside in the plot, as previously described (Mark and Rowley, 1969), were continued until May 1970.

A fifth triplicate set of non-weighing lysimeters with bare soil was installed at the southern end of the 75 × 25 m plot in the original burned area, in September 1970. Solar radiation was measured with a Belfort Instrument Coy actinometer* from October 1966 onwards, wind speed at a height of 2 m has been recorded with a Casella three-cup anemometer from October 1968, and soil temperature extremes at -10 cm have been measured since December 1969 with a Zeal U-type maximum-minimum thermometer (range $-24°$ to 54°C) as previously described (Mark, 1965a). A Foxboro 0–1.5 m water-level recorder monitored outflow from one of the normal snow tussock tanks between May 1969 and March 1970, and the patterns were related to rainfall duration and intensity as measured with a Sumner two-pen temperature/rainfall recorder (Sumner, 1959). Such rainfall records were also compared with values obtained by an adjacent pair of Casella recording raingauges on which had been mounted either a cylindrical Grunow-type fog interceptor 20 cm long and 8.3 cm in diameter as described by Dreaver (1971), or 32 snow tussock tillers mounted and held erect (Fig. 2) as described earlier (Rowley, 1970).

The snow tussock transpiration experiment previously described (Mark and Rowley, 1969) was repeated in 1969–70 because of the poor recovery of burned tussocks in the earlier study. Nine tussocks,

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* The borosilicate glass dome of this instrument transmits 90 percent of all wavelengths from 0.36 to 2.0 μm, 50 percent at *c.* 3.3 μm, and 20 percent at 4.0 μm. U.V. radiations are cut off at 0.2 μm.

FIG. 1 — The three untreated snow tussocks in lysimeters among unmodified snow tussock grassland at the north end of the plot. Arrows point to the projecting rim of each lysimeter.

FIG. 2 — Recording raingauges at the study site to compare catches of a fog interceptor (right) and 32 mounted snow tussock tillers (left) with that of a conventional gauge. April 1970.

c. 90 cm tall with a basal diameter of *c.* 25 cm and a maximum canopy spread of *c.* 100 cm, were brought to Dunedin from the study area in May 1969 and their transpiration measured, for standardization purposes, for 11 weeks. Correction factors ranged from 0.65 to 1.28 and were used to select representative triplicates for clipping or burning in mid August. Transpiration of the clipped, burned and normal tussocks was then measured for 35 weeks, together with evaporation from duplicate porous pots both beneath the polythene screen among the tussocks and beyond it (see Mark and Rowley, 1969, Fig. 2). On completion of this experiment the tillers in each tussock were counted and 10 from each randomly sampled to determine green leaf area as described by Kemp (1960) and then oven dried (100°C for 24 hours) for estimates of total area and weight of green leaf in each tussock.

With the burned and clipped snow tussocks at the field site apparently fully recovered after six years, the original non-random layout was abandoned at the end of September 1972. Similar-sized snow tussocks from the vicinity were then transplanted to all 15 lysimeters and maintained for one year when the previous treatments (normal, burned and clipped snow tussocks, a blue tussock sward and bare soil) were reintroduced, but this time arranged randomly. The surrounding tussocks in the fenced plot, however, were not treated again at this time. After one year with this layout the 15 tanks were calibrated using bare soil throughout. Seven months' data are now available

Precipitation from seven sites below the study area and four above it, which span the full altitudinal and vegetational sequence of the Range, has been recorded monthly since 1969. Values for the study area can therefore be related to the altitudinal pattern on the southeastern slope of the Range.

RESULTS

The Environment

Deviations from long-term annual precipitation at the nearest official station (Garthmyl, 198 m) *c.* 11 km south of the lowest station, for each of the five years, have been applied to the annual catches at each of the 13 sites on the Range in order to estimate their long-term values. Not surprisingly, the variation in estimates over the five-year period tends to increase with both altitude and precipitation (Fig. 3). The estimated long-term mean annual precipitation for the study area, based on the five-year period, is 1320 mm which Duncan's New Multiple Range Test (Duncan,

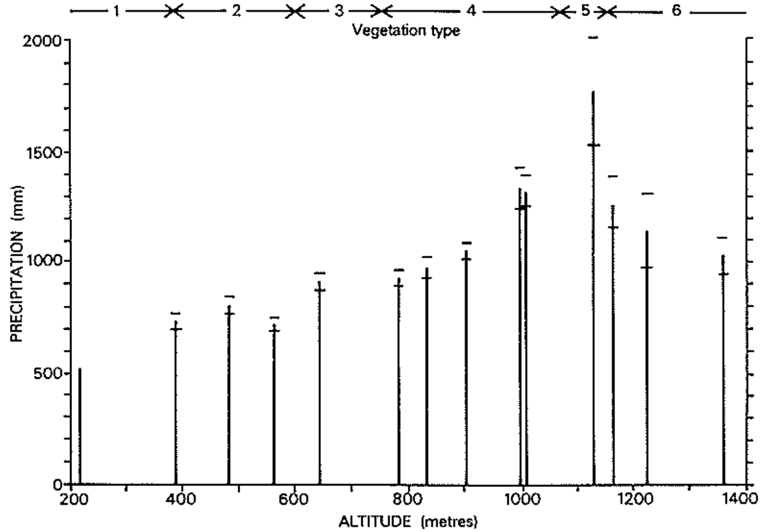


FIG. 3 — Estimated mean annual precipitation for 13 sites on the south-eastern slope of Rock and Pillar Range. The long-term mean value for the nearest official station, Garthmyl, is shown on the left. The horizontal lines on the remaining 13 values indicate variations in the estimation of their long-term mean values for each of the six years, using deviations for Garthmyl as the basis for estimation. Vegetation types associated with the altitudinal series are indicated at the top: 1=exotic; 2=montane fescue tussock grassland; 3=subalpine mixed fescue/snow-tussock grassland; 4=low-alpine snow tussock grassland; 5=subalpine mixed scrub; 6=high-alpine herbfield and cushion vegetation.

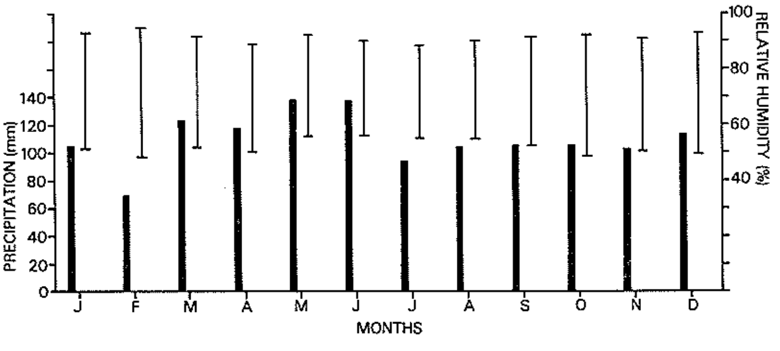


FIG. 4 — Mean monthly precipitation (histograms) for an eight-year period (October 1966 to September 1974) and mean daily maximum and minimum relative humidities for each month for a six-year period (October 1966 to September 1972) for the study site, *c.* 1000 m, Rock and Pillar Range.

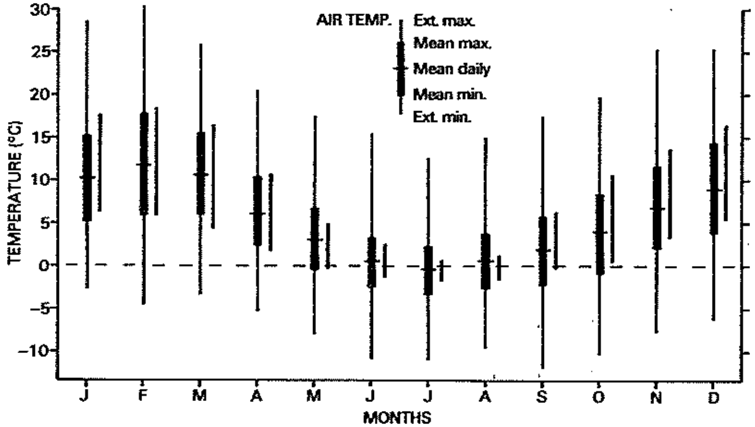


FIG. 5 — Mean monthly air (+1.2 m) and soil (—10 cm) temperatures for the study site at *c.* 1000 m, Rock and Pillar Range. Five air temperature values are shown as indicated, based on six years of data (October 1966 to September 1972). The simple columns indicate the mean monthly range of soil temperatures for a three-year period (January 1970 to September 1972).

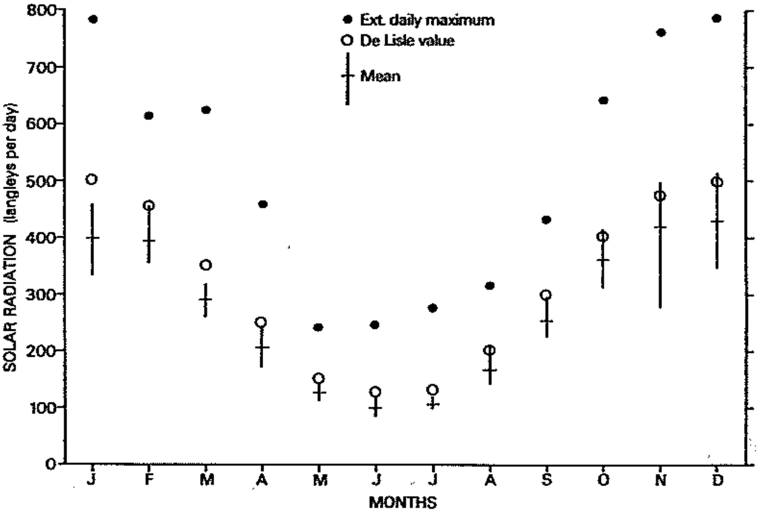


FIG. 6 — Monthly solar radiation values, as indicated, for the study site at *c.* 1000 m, Rock and Pillar Range, based on six years of data (October 1966 to September 1972). Values calculated by de Lisle (1966) for the Rock and Pillar region have been included.

1955) indicates is not significantly different ($P < 0.05$) from that of one station below (905 m) and three above (1165 m, 1225 m and 1360 m).

Estimated mean annual precipitation along the altitudinal transect on the Rock and Pillar Range reaches a maximum *c.* 130 m above the study area in the narrow zone of subalpine scrub (Fig. 3). The decrease recorded beyond this elevation, however, is likely to be due, at least in part, to increased wind speed (Bliss and Mark, 1974).

Eight years of monthly precipitation records from either end of the 75×25 m fenced plot at the study area show no significant difference. Mean monthly values for the eight years (Fig. 4) indicate a slight maximum in early winter and a more pronounced minimum in February although those for the first six years, on which the main water-balance study is based, show somewhat greater variation (Fig. 11). Mean monthly values for air and soil temperatures (Fig. 5), solar radiation (Fig. 6), relative humidity (Fig. 4), wind speed (Fig. 7) and potential evapotranspiration (PE) (Fig. 8) are presented to characterize the site. PE values for equivalent grass turf and Thornthwaite (1948) determinations were calculated as described previously (Rowley, 1970) except that evaporimeter values for June–September have been based on loss of 20 percent ethanol in distilled water, adjusted to equivalent distilled-water loss by a correction factor (×0.87) as recommended by Cooper (1970).

Soil moisture availability recorded with gypsum blocks and a Bouyoucos meter (model BN-2B) usually exceeded 95 percent, both within the lysimeters and outside in the grassland, and never fell below 88 percent except when the soil froze. Such values confirmed those obtained earlier with gravimetric determinations that soil

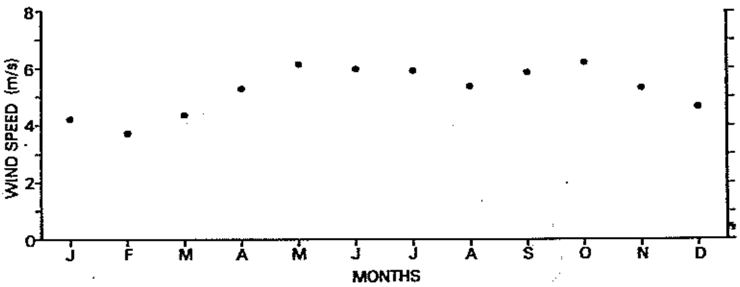


FIG. 7 — Mean monthly wind speed measured at a height of 2 m at the study site on the Rock and Pillar Range for a three-year period (January 1970 to September 1972).

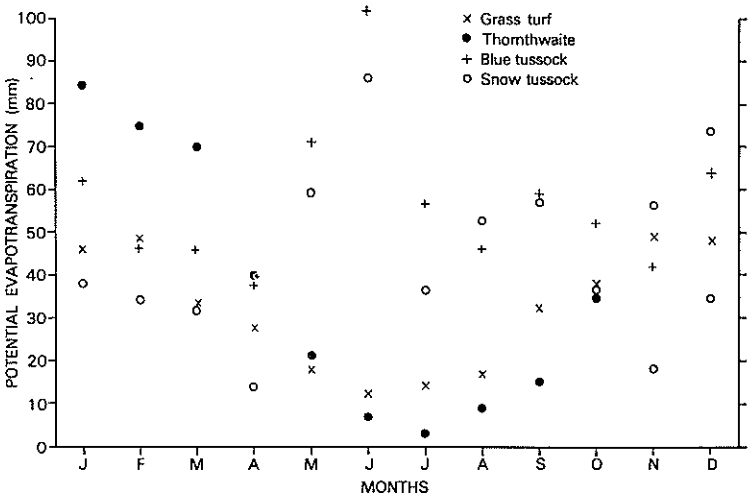


FIG. 8 — Mean monthly potential evapotranspiration for the study site at *c.* 1000 m, Rock and Pillar Range. Thornthwaite estimates and values for the blue tussock turf and normal snow tussock are based on six years of data (October 1966 to September 1972), those for grass turf equivalent on three years (January 1970 to September 1972).

moisture is non-limiting; therefore evaporative loss of water from the lysimeters would occur at potential rates. Single correlation coefficients were determined between each pair of environmental factors using the monthly values (Fig. 9).

Water Balance

The water balance is assumed to be expressed by the equation:

$$PE = \text{precipitation} - \text{throughput} \pm \text{storage}$$

where potential evapotranspiration (PE) is assumed to be the difference between the precipitation and the throughput. The storage component is the difference in amount of water stored in the lysimeter which, under the conditions prevailing at the site, can probably be ignored.

The annual throughput or water yield associated with normal snow tussock, burned snow tussock, clipped snow tussock, blue tussock sward and bare soil for each of the six yearly periods (the latter for only the last two years), are shown and compared with precipitation in Fig. 10. Comparable value for the same five treatments in the randomized design (1973–74) are shown to the right of this figure. Among the treatments, only the difference in

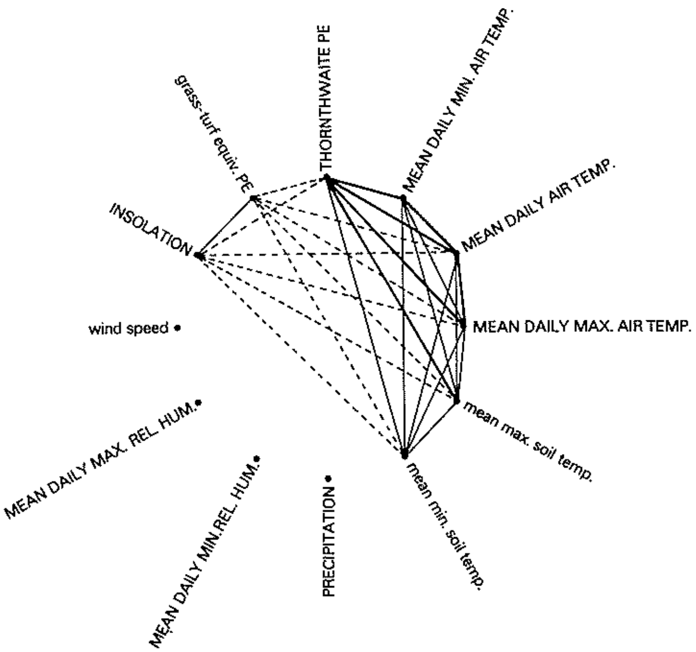


FIG. 9 — Simple correlation coefficients between each pair of 12 environmental factors, using monthly values recorded at the study site at *c.* 1000 m, Rock and Pillar Range. Capitals indicate 72 months of data, lower-case letters indicate 34 months. Heavy lines $r=0.95$ to 0.99; light lines $r=0.90$ to 0.95; dashed lines $r=0.70$ to 0.90.

annual throughput between normal snow tussock and the blue tussock sward was significant ($P < 0.05$) over the six years. In addition the relative throughputs among the five treatments did change with time. Of this treatment/year interaction ($P < 0.001$), 40 percent is due to linear changes in the differences between the treatments. This was true looking at either throughput as such, PE (precipitation minus throughput) or the proportion of precipitation which was measured as throughput. Mobility of snow in winter (Fig. 12) may obscure the relation between precipitation and throughput, but excluding the three winter months from the analysis hardly altered the results. Regression of the difference between the burned and normal tussocks on time showed a significant decrease over the period, and since this was not so for the blue-tussock treatment it seems that the changes in the relative throughputs of the treatments were due to the recovery of the burned tussocks.

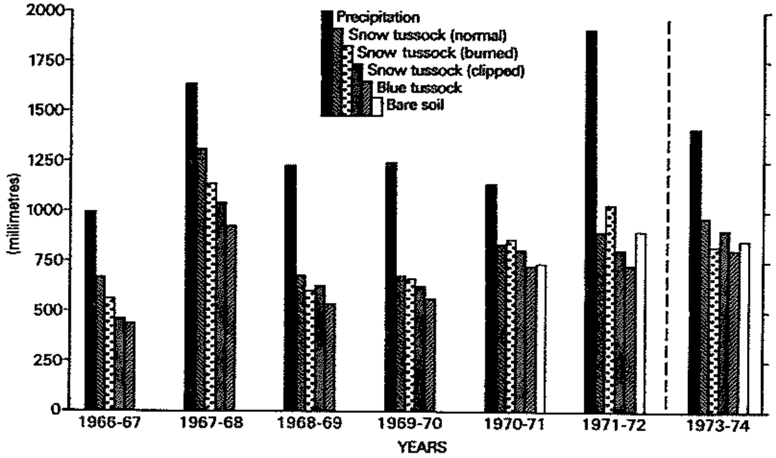


FIG. 10 — Total annual precipitation and mean water surplus (=yield or throughput) for triplicate lysimeters containing five treatments, for a six-year period (but bare soil for only a two-year period). Values for 1973–74 are for the same treatments but randomly distributed among the 15 tanks. Annual periods are October to September in all cases.

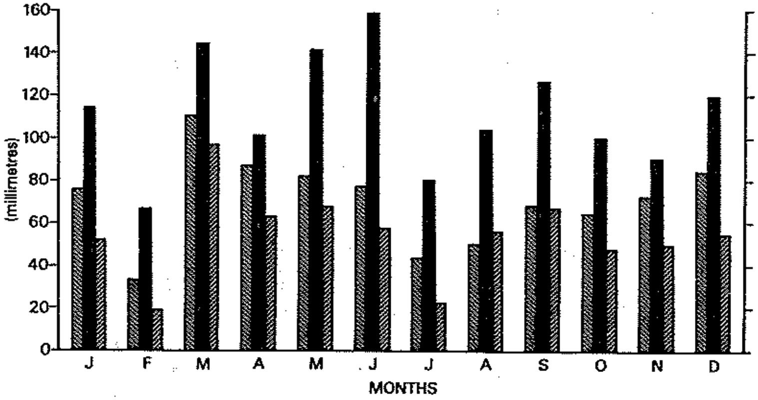


FIG. 11 — Mean monthly precipitation (solid columns) and throughput (yield) of lysimeters containing normal snow tussocks (left) and a blue tussock sward (right) for a six-year period (October 1966 to September 1972). PE values are the difference between those for precipitation and the respective throughputs.

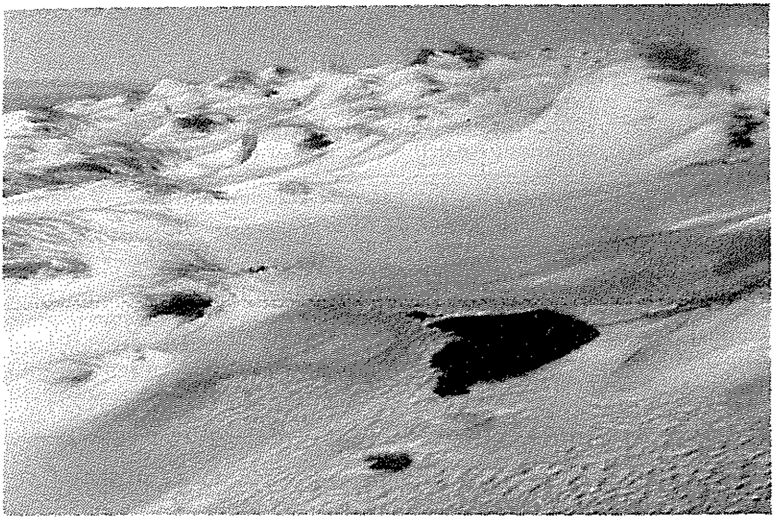


FIG. 12 — Variation in depth of snow caused by its redistribution related to presence or absence of a snow tussock cover. Site adjacent to study area. 29 June 1975.

The trend with time was further investigated by separate analyses of variance of the data for three two-year periods. Throughput for the first two-year period showed significant treatment differences ($P=0.016$), as reported previously (Mark and Rowley, 1969), while neither the second nor third periods showed significant differences. Duncan's New Multiple Range Test shows that the only difference in throughput for the first two-year period was between the normal snow tussocks and the blue tussock sward (Table 1). Throughputs for the one-year random layout of treatments confirmed the significance of this difference as well as between the normal and burned snow tussocks (Table 1), while values for the full seven years are also given even though they could not be treated statistically because of rearrangement of the set-up.

Throughput under bare soil, being available for only three years (Fig. 10), has not been analysed in detail. The mean annual value was 830 mm or 56 percent of the precipitation, a value which was confirmed (55 percent) when all 15 lysimeters were calibrated using bare soil over a seven-month period. This calibration showed no significant differences between the triplicated tanks containing the four original treatments, although the fifth set, installed later for bare soil treatment, produced a significantly smaller throughput. That one year's throughput values when normal snow tussocks

TABLE 1 — Mean annual throughput of water (mm) in four sets of triplicated lysimeters, with different plant cover for: the first two-year period of study; the one year with random layout of treatments; the full seven-year period. Mean annual precipitation for the periods was 1280 mm, 1415 mm, and 1357 mm, respectively. Significant differences (Duncan's New Multiple Range Test) are indicated where applicable by absence of letters in common (capitals at $P < 0.01$, lower case at $P < 0.05$).

	First 2 years		*1-yr random layout*		*7 years*
	Mean ann. throughput (mm)	*Signif. diff.*	*Mean ann. throughput (mm)*	*Signif. diff.*	*Mean ann. throughput (mm)*
Normal snow tussock	986	A a	974	A a	863
Clipped snow tussock	744	A ab	918	A a	754
Burned snow tussock	853	A ab	825	A b	816
Blue tussock sward	687	A b	813	A b	677

occupied all 15 tanks showed a different pattern (Table 2) from that obtained with bare soil highlights the difficulty of obtaining matched tussocks for such a study. Mean throughput from the 15 tanks containing normal snow tussocks for a yearly period was 586 mm, or 58 percent of the 1012 mm precipitation.

On a mean annual basis for the six-year period, precipitation amounts to 1348 mm, of which 844 mm or 63 percent is surplus (throughput or yield) in the normal snow tussock lysimeters compared with 656 mm or 49 percent in the blue tussock tanks. Values for the lysimeters containing snow tussocks that had been initially burned or clipped are intermediate, being 815 mm (60 percent) and 726 mm (54 percent), respectively.

In order to relate the several environmental parameters measured to water-use (PE) values a multiple-regression analysis of monthly use by the normal snow tussocks and the blue tussock sward was made with monthly values for 12 environmental factors. Only eight factors could be analysed for the full 72 months, so a separate analysis was carried out for all 12 on the last 34 months of the study. The whole regression was significant in both analyses ($P = < 0.001$). Snow tussock PE values were significantly related in the expected directions to insolation, precipitation and mean daily minimum relative humidity over the 72-month period, the whole regression accounting for 58 percent of the variation. However, a step-down predictive regression involving these three factors plus air temperature minima account for 53 percent of the variation. Analysis of the 34-month period showed additional significant effects of Thornthwaite PE, wind speed and minimum soil temperatures, and this 12-variable regression could account for 89 percent

TABLE 2 — Throughput of water (mm) in five sets of triplicated lysimeters, each containing similar-sized normal snow tussocks, for the one-year period October 1972 to September 1973. Precipitation for the year was 1012 mm. The previous treatments in each of the five triplicated sets have been indicated. Values lacking a letter in common are significantly different (capitals at $P<0.01$, lower case at $P<0.05$), according to Duncan's New Multiple Range Test.

Previous treatments	*Mean ann. throughput from normal snow tussocks (mm)**	*Signif. difference*
Bare soil	637	A a
Normal snow tussock	618	A a
Burned snow tussock	638	A a
Clipped snow tussock	551	ABab
Blue tussock sward	489	B b

* Mean of three values.

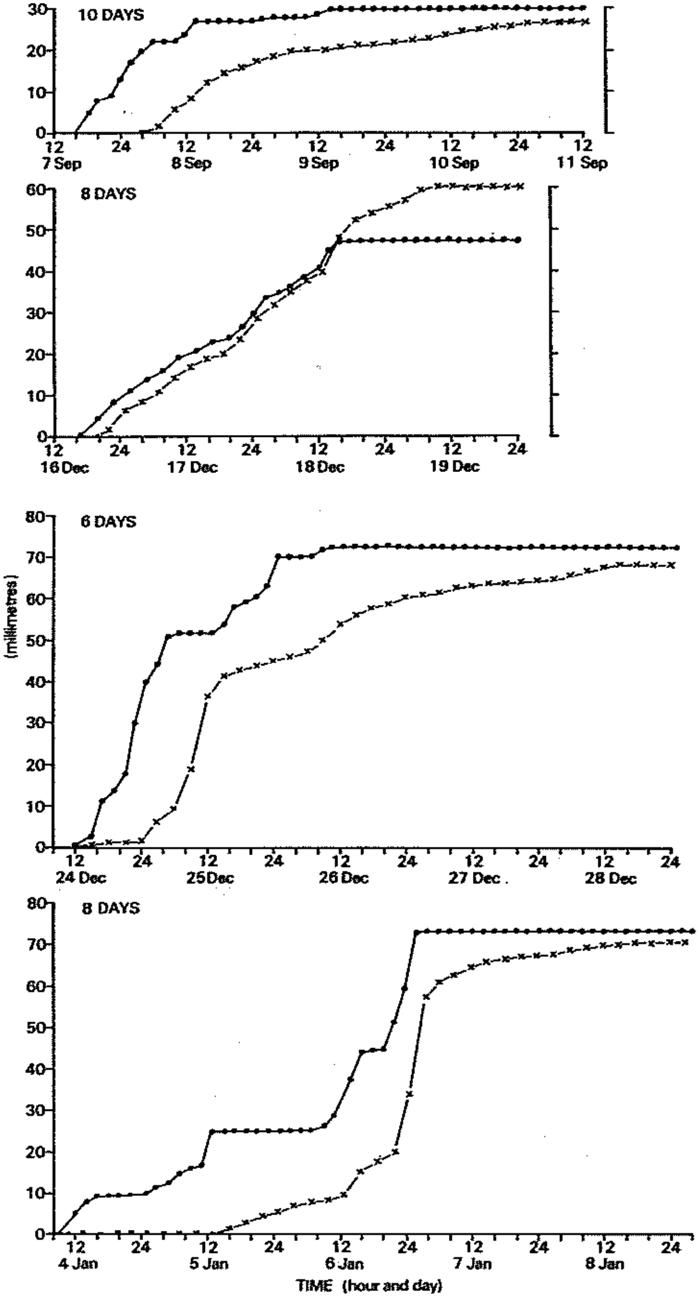
of the variation. Blue tussock PE values for the 72-month period were significantly related to Thornthwaite PE, minimum relative humidity and precipitation. The regression accounts for 69 percent of the variation, with the three significant factors accounting, in a step-down predictive regression, for 67 percent of the variation. Over the 34-month period, additional significant factors were wind speed and both extremes of soil temperature.

Patterns of Precipitation and Discharge from the Solum

The discharge of gravitational water from a lysimeter containing a normal snow tussock was related to duration and intensity of precipitation, as measured by the Sumner recorder's tipping bucket during the 1969–70 season. Results for five storms have been presented (Fig. 13) to show the range of responses recorded. Exact synchrony between the two instruments was not always possible, so the duration of the delay between precipitation and discharge shown in Fig. 13 should not be taken as precise. Gravitational flow persisted for up to three days beyond cessation of most storms and in all cases released almost the equivalent of the precipitation measured. In one case (16–19 December) the amount discharged exceeded the precipitation recorded (by 12 mm), the surplus probably representing interception gained from fog by the tussock canopy (see below).

Interception Gains by a Snow Tussock Canopy

Patterns of water catch in adjacent recording raingauges on which either an equivalent snow tussock or a fog interceptor was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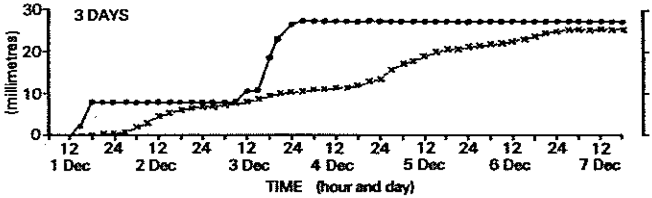

FIG. 13 (*above and opposite*) — Comparisons of precipitation patterns (duration and intensity) (●——●) with those of water discharge from a lysimeter (X——X) containing a normal snow tussock for five 'storms' at 1000 m, Rock and Pillar Range. 1969–70 season. The value of days shown in the top left is the period since rain in excess of 5 mm fell at the site.

mounted, are compared with that from a standard gauge for six 'storms' in Fig. 14. Amounts recorded with the fog interceptor were two to eight times that collected by the standard gauge, while the snow tussock leaves increased the catch by factors of 10 to 36 over periods of one day or less. Although the results shown are the most dramatic obtained during the three months of recording (23 December 1969 to 30 March 1970), they clearly indicate the ability of a snow tussock canopy to substantially supplement water input to the soil under certain conditions.

Transpiration

The mean weekly transpiration rates at Dunedin for normal snow tussocks and those recently burned or clipped are compared with grass-turf-equivalent PE values (obtained from a pair of evaporimeters placed among the tussocks) for a 35-week period, in Fig. 15. The normal tussocks had the highest rates, except for the last eight weeks when they were equalled or occasionally exceeded by losses from the clipped tussocks. The burned plants maintained lower rates throughout. Variations in transpiration generally followed those of PE except for the treated tussocks during the initial recovery period. Table 3 shows that maximum transpiration rates in the normal and clipped tussocks were reasonably close to those recorded at the same site a year earlier by Mark and Rowley (1969). The increase in transpiration of the burned tussocks compared with the earlier results is associated with their better recovery in the current study. Differences in number of tillers, in area and dry weight of green leaves, and in transpiration per unit leaf area per day between the three treatments are given in Table 3.

Analysis of variance of water loss in seven periods, each of five weeks duration, showed that during the first 15 weeks transpiration rates were not significantly different between burned and clipped tussocks but only between these and the normal plants. From the 15th to 20th weeks, however, differences between burned and clipped tussocks became significant, and this was maintained until the experiment ended. At this time, rates from the clipped and

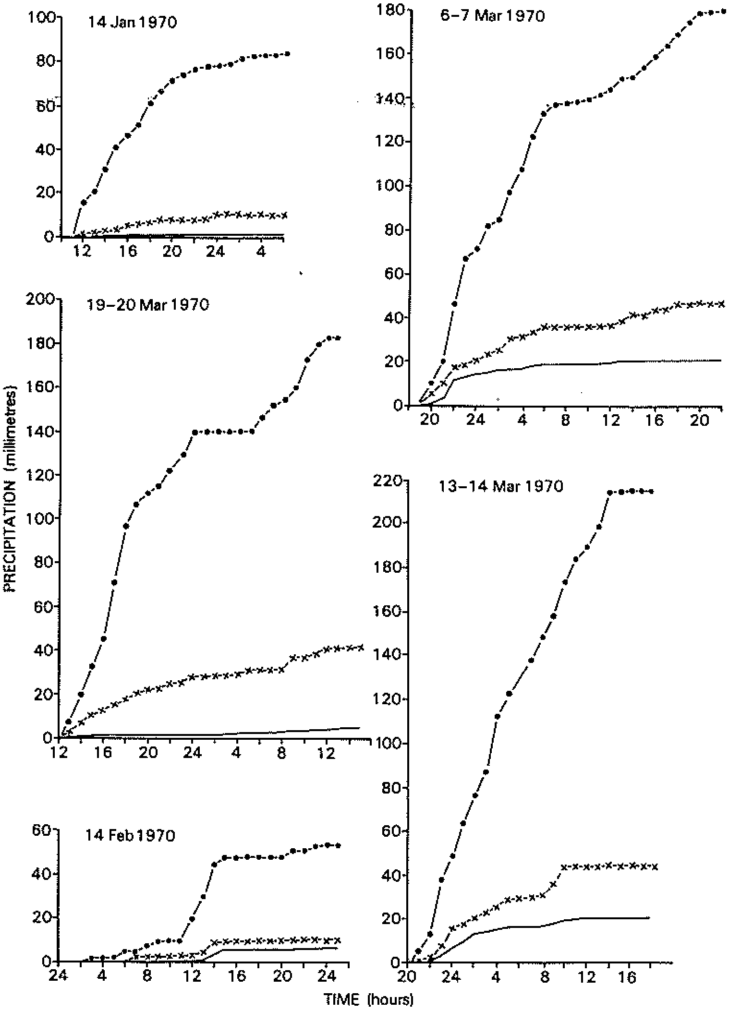

FIG. 14 — Comparisons for five 'storms' of precipitation caught with a standard recording gauge (solid line), and with a cylindrical wire-gauze fog interceptor (X——X) or snow tussock tillers (●——●) mounted on the gauge.

normal tussocks were not significantly different. PE values measured among the tussocks were *c.* 15 percent less than on the open lawn alongside and *c.* 35 percent less than at the field site. Burning and clipping both apparently reduced the number of tillers per tussock although both the green leaf area and dry weight of green leaves in the clipped plants were similar to that of the normal tussocks (Table 3). Transpiration rates per unit leaf area were lowest in the normal plants and highest in those recovering from burning.

TABLE 3 — Number of tillers, areas and dry weights of green leaves, and transpiration rates (ml/day) for normal snow tussocks and those recently burned or clipped. Maximum transpiration recorded by Mark and Rowley (1969) for the same site in Dunedin are given for comparison.

Snow tussock treatment	*Mean value per plant**			*Transpiration (ml/day)*			
					Per plant		
	No. tillers	*Green leaf area* (m^2)†	*Green leaf dry wt. (g)*	*Per* m^2†	*Mean*	*Max.*	*Max.*‡
Normal	189	0.889	67.5	40.8	200	299	300
Clipped	98	0.811	73.5	44.6	138	268	187
Burned	91	0.456	38.5	46.8	102	188	57

* Determined at end of transpiration experiment.
† Based on one leaf surface only and for last three weeks of study.
‡ Data from Mark and Rowley (1969).

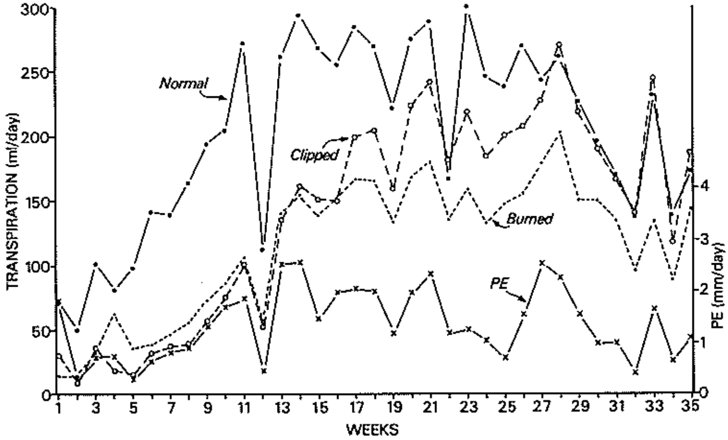

FIG. 15 — Mean daily transpiration rates for normal, burned and clipped snow tussocks at Dunedin compared with grass turf equivalent potential evapotranspiration. The weeks shown are from the beginning of the experiment on 18 August 1969.

DISCUSSION AND CONCLUSIONS

It is standard practice in lysimetry, when soil moisture is non-limiting, to calculate PE as the difference between water intake measured with a raingauge and the surplus water discharged (Sutcliffe, 1968). And since the mean area occupied by a snow tussock at the field site (0.34 m^2) is only slightly greater than the area of the improvised non-weighing lysimeters (0.25 m^2), the values obtained with single snow tussocks should be reasonably representative of a unit area of snow tussock grassland.

Results of the six-year study differ somewhat from those predicted earlier on the basis of the first two years' results (Mark and Rowley, 1969) but the overall conclusions have been generally substantiated. The mean annual precipitation of *c.* 1348 mm is partitioned differently according to the type and condition of plant cover. Under normal (undamaged) snow tussocks 63 percent of this precipitation is surplus, being measured as throughput, leaving 37 percent as the PE loss. A blue tussock sward consumes almost half (49 percent throughput and 51 percent as PE), while values for snow tussocks that had been initially defoliated are intermediate (60 percent throughput and 40 percent PE with the burned tussocks; 54 percent throughput and 46 percent PE following clipping). Comparable values for bare soil are less reliable, being based on only two years' data, but the value obtained (56 percent throughput) was confirmed when all 15 tanks were calibrated using bare soil for a seven-month period.

Several other factors, however, operating independently and differentially, complicate the situation and make such simple estimations questionable. These factors include substantial interception gains, particularly from fog, redistribution of precipitation by individual snow tussocks, transpiration losses, and snow accumulation and retention.

Measurement of interception gains, both in the present study and earlier (Rowley, 1970) indicate that they increase with the height of a tussock. Interception capacity of normal snow tussocks far exceeds the catch of a standard raingauge or of a fog interceptor and obviously may result in a substantial increase in the water intake to a unit area of grassland soil. Redistribution of precipitation by individual snow tussocks (Rowley, 1970), on the other hand, probably is relatively unimportant in modifying the total water input to such a unit area.

Normal snow tussocks obviously expend substantial amounts of water in their transpiration. Rates in such plants, containing *c*. 190 tillers, which provide *c*. 0.89 m^2 (one surface only) or 68 g of green leaf material, amounted to *c*. 250 ml per day under the experimental conditions at Dunedin. Differences in evaporative loss between the Dunedin site and that on Rock and Pillar Range suggest that such tussocks could consume *c*. 340 ml a day at the field site during midsummer, or about 10 litres a month. This is greater than the 7.5 litres per month derived from an earlier assessment of identical design (Mark and Rowley, 1969). Together they indicate a midsummer consumption of 30 to 40 mm of precipitation per month by a normal snow tussock in the lysimeter, values which are within the range of those actually measured for the December–February period.

Transpiration rates of clipped tussocks reached those of normal plants by the end of the first season whereas burned tussocks, despite a higher rate per unit leaf area, appear to require more than one season. The relatively rapid regrowth following either burning or clipping (Mark, 1965b), which allows transpiration rates to recover within one or two seasons, may not fully restore the interception capacity to that of a normal tussock since total leaf length is less, in part because of absence of their long dead tips. Also, compensating effects in terms of a water balance, between the transpiration losses and interception gains of snow tussock leaves, would reduce the difference in annual water surplus between normal tussocks and those recovering from a recent defoliation. Nevertheless, the annual water yield was somewhat greater under the normal tussocks than under those recently burned or clipped, and the burned tussocks did show a significant upward trend in water yield over the six years. The blue tussock sward was associated with a significantly smaller throughput than the normal snow tussocks over each of the six years. Even though this could be due in part to the reduced ability of the short grass turf – compared with a tall canopy of snow tussocks – to retain snow during winter, it is a feature which persists throughout the year and is probably due largely to negligible interception gains by a blue tussock sward. Transpiration rates higher than the same unit area of snow tussock grassland appear unlikely, although neither interception nor transpiration of blue tussock has yet been measured.

Although precipitation was not significantly different between opposite ends of the plot, an obvious shortcoming of the study is the non-random distribution of the five treatments among the 15 lysimeters. One year's data from the same five treatments randomly distributed did, however, confirm the difference in throughput between normal snow tussocks and both a blue tussock sward and recently burned snow tussocks, indicating that these are real effects. Short-term calibration of the 15 lysimeters, using either bare soil or normal snow tussocks, gave inconsistent results which probably highlight the difficulty of selecting tussocks of similar performance.

The information obtained thus reinforces the tentative conclusions offered after the first two years of this study: that "the maximum water yield (and control) from the low-alpine snow tussock grasslands is obtained from natural undisturbed cover" (Mark and Rowley, 1969).

With an increasing acceptance of water as potentially the most valuable product from most high mountain areas of New Zealand, particularly hydro-electric catchments and the water-deficient Taieri catchment where this study was made, there is an urgent need to extend this type of study to a greater range of vegetation and condition types, but with somewhat larger lysimeters or preferably a series of small comparable water-tight catchments. Extending the range of altitudes would also be desirable, but difficulties are likely to increase at both higher and lower elevations. At lower altitudes the chief problem could be in differentiating between actual and potential evapotranspiration. Problems of coping adequately with snow, combined with high wind speeds and with more persistent and deeper penetration of frosts at higher altitudes (Bliss and Mark, 1974), would probably add substantially to the difficulties encountered in such a study.

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REFERENCES

Bliss, L. C.; Mark, A. F. 1974: High-alpine environments and primary production on Rock and Pillar Range, Central Otago, New Zealand. *N.Z. Journal of Botany 12*: 445–483.

Cooper, K. M. 1970: The use of ethyl alcohol as an antifreeze in porous pot evaporimeters. Unpublished manuscript, Botany Department, University of Otago. 26 p.

de Lisle, J. F. 1966: Mean daily insolation in New Zealand. *N.Z. Journal of Science 9*: 992–1005.

Dreaver, K. R. 1971: The accuracy of rain gauges under exposed conditions. M.Sc. thesis, University of Otago. 70 p.

Duncan, D. B. 1955: Multiple range and multiple *F* tests. *Biometrics 11*: 1–42.

Kemp, C. D. 1960: Methods of estimating the leaf area of grasses from linear measurements. *Annals of Botany 24*: 491–499.

Mark, A. F. 1965a: The environment and growth rate of narrow-leaved snow tussock, *Chionochloa rigida,* in Otago. *N.Z. Journal of Botany 3*: 73–103.

Mark, A. F. 1965b: Effects of management practices on narrow-leaved snow tussock, *Chionochloa rigida. N.Z. Journal of Botany 3*: 300–319.

Mark, A. F.; Rowley, Jennifer 1969: Hydrological effects in the first two years following modification of snow tussock grassland. *Lincoln Papers on Water Resources 8*: 188–202.

Rowley, Jennifer 1970: Lysimeter and interception studies in narrow-leaved snow tussock grassland. *N.Z. Journal of Botany 8*: 478–493.

Sumner, C. J. 1959: Single-pen strip chart recorder for unattended long period operations. *Journal of Scientific Instruments 36*: 475–477.

Sutcliffe, J. F. 1968. *Plants and Water.* Arnold, London. 81 p.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. *Geographical Review 38*: 56–94.