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Tussock grasslands and high water yield: a review of the evidence

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Abstract

Two hypotheses have been proposed to account for sustained high water yields in tussock grassland of upland east Otago: low evaporation and fog interception. We examine the evidence for the relative importance of the two mechanisms. Weighing lysimeter studies and those measuring snow tussock transpiration all suggest that restricted transpiration is responsible for high water yields from tussock grassland, despite the potential for tussocks to transpire more freely. Snow tussock appears to start controlling its transpiration rate through shutting stomata as the atmospheric demand for water vapour increases (i.e., an increase in saturation vapour pressure deficit). When this is combined with modest wet leaf evaporation, or canopy interception loss, it is clear that snow tussock is conservative in its use of water. A recent analysis of the isotopic signatures of rainfall, fog and water collected at the base of lysimeters suggests that water draining from the soil is a mix of rain and fog in sub-equal proportions. We offer other, equally valid, explanations for the same results that do not lead to the conclusion that fog deposition makes a substantial contribution to water yield. There is no evidence from catchment studies undertaken in the east Otago uplands to suggest that fog deposition is capable of augmenting water yield from tussock grasslands. We conclude that low evaporation from tussock grassland, especially during dry periods, is much more likely to explain the high water yields at both the plant and catchment scale.

Keywords

Tussock grassland, water yield, fog deposition, evaporation.

Introduction

Tussock grasslands provide an iconic landscape feature for much of the high country in the South Island of New Zealand. They are considered to be important from a water resource management perspective, as catchments covered in snow tussock (*Chionochloa rigida*) have higher water yields than those with pasture grass or forestry land covers. A combination of landscape and water yield arguments has been used to justify the establishment of conservation reserves for some areas of tussock uplands, an example of which is Te Papanui in the Lammerlaw and Lammermoor ranges, west of Dunedin.

The notion that a tussock grassland cover is important in sustaining high water yields was first suggested by Mark and Rowley (1969). Since then there have been several studies looking at water yield from tussock-covered catchments (e.g., Pearce *et al.*, 1984; Bonell *et al.*, 1990; Fahey and Watson, 1991; Bowden *et al.*, 2001; Duncan and Thomas, 2004). The debate over the mechanisms responsible for the high water yields from tussock-lands by and large falls into two camps, one advocating low evaporation from tussocks (e.g., Campbell, 1989; Campbell and Murray, 1990; Fahey *et al.*, 1996), and the other advocating fog interception by tussock canopies (e.g., Holdsworth and Mark, 1990; Ingraham and Mark, 2000).

This paper brings together the research into water yields from tussock grasslands in east Otago in a single review to identify the relative importance of the contributing mechanisms, and to assist resource managers in understanding the science behind the arguments. We first give a brief overview of the evidence for the two points of view, then provide a more detailed discussion.

Tussocks and evaporation

Much of our understanding regarding water yield from the tussock grasslands of east Otago is based on research undertaken at the Glendhu experimental catchments in the upper Waipori River basin northwest of Lawrence (Fig. 1). These were established as a paired catchment study in 1980 to investigate the streamflow behaviour and water balance of lightly grazed tussock grassland, and to assess the effect of afforestation on tussock grassland hydrology. One catchment (GH2, 310 ha) was planted in *Pinus radiata* in 1982, and the other (GH1, 218 ha) was left in tussock grassland as the control. Pearce *et al.* (1984) examined the flow record of the two catchments in the pre-treatment period (1980–1982) and found both to sustain high flow rates between storms. Modelled evaporation (using Penman and Priestley-Taylor calculations) was found to be markedly higher than evaporation calculated as a residual from the catchment water balance. Pearce *et al.* (1984) hypothesised that the discrepancy was a result of low transpiration rates from the tussock. They conclude that the "*low transpiration values are also consistent with the observed high, persistent rates of delayed runoff from shallow, unconfined groundwater storage*" (Pearce *et al.*, 1984, p. 71).

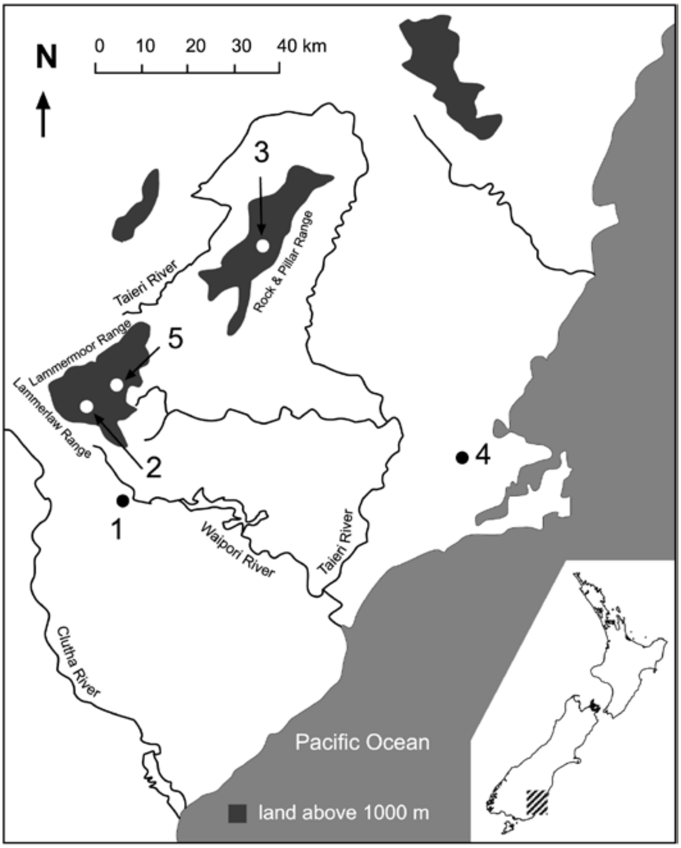

Figure 1 – Location of main study sites referred to in text: 1) Glendhu study catchments; 2) Lammermoor site of Ingraham and Mark (2000); 3) Rock and Pillar site of Ingraham and Mark (2000); 4) Swampy Summit; 5) Deep and Elbow Creeks of Duncan and Thomas (2004).

Plants show differing abilities to control their stomata when placed under water stress. Pasture species have a poor coupling with the atmosphere (Jarvis and McNaughton, 1986) and continue transpiring at a fast rate when there is a large saturation vapour pressure deficit. Other plants, including snow tussock, are well connected with the atmosphere and shut down their stomata when under limited water stress from atmospheric conditions, resulting in low transpiration rates. Pollock (1979) showed that under glasshouse conditions snow tussock is able to control stomata and therefore transpiration rates. Campbell (1989) measured evaporation rates above a tussock canopy using a large (5.8 m^2) weighing lysimeter. The dry leaf evaporation (transpiration) rate was strongly linked to the atmospheric saturation vapour pressure deficit (i.e., the transpiration rate decreased as the atmospheric demand increased). Campbell and Murray (1990) suggested that this process could explain why their lysimeter-based estimates of transpiration from snow tussock were so low. The ability of different plant species to control evaporation through reduced transpiration has been shown in other situations where the available water is not limiting (e.g., in wetlands, Campbell and Williamson, 1997; Thompson *et al.*, 1999).

Holdsworth and Mark (1990) measured relatively high rates of evaporation loss from snow tussock with non-limited soil moisture conditions in a glasshouse. This shows that tall tussock has potentially high transpiration rates when not under stress. The rates are not as high as for pasture, but are higher than rates for other native species such as blue tussock.

Espie and Grau (1994) used an infrared gas analyser in isolation chambers situated over *in situ* tussocks in the Deep Stream and Deep Creek catchments in the Lammermoor Range of upland east Otago to confirm that actual transpiration rates from snow tussocks were low. Espie and Grau (1995) further showed that the measured snow tussock transpiration values closely match those estimated by measurements using a weighing lysimeter on Swampy Summit near Dunedin (Fahey *et al.*, 1996).

Duncan and Thomas (2004) analysed flow data from two tussock grassland catchments (Deep Creek and Elbow Creek) in the Lammermoor Range, Otago, to investigate the hydrological impact of fire as a land management option. The two catchments are located within 3 km of each other on opposite sides of the Lammermoor Range divide (Fig. 1). Both range in elevation from 900 to 1100 m, have a comparable geology and soil cover to the Glendhu catchments 20 km to the south-east, and, like their Glendhu counterparts, are characterised by headwater and riparian wetlands. The rainfall regime is also similar, consisting of many small events of long duration and low intensity. They do, however, have much more snowfall, which makes access difficult and precipitation and runoff measurements unreliable in the winter. Measurements of rainfall and runoff began in 1980, and in 1988 80% of the tussock cover of Deep Creek was burnt. Water yields for the period November to April were predicted from a regression equation describing the relationship between the summer water yields of the two catchments before burning. After the tussock cover was burnt, summer water yields declined relative to the control catchment, i.e., the evaporation increased. The greatest decline was observed two summers after the spring burning, after which the impact lessened. This was attributed to increased transpiration during the period of rapid tussock tiller regrowth following fire.

Tussocks and fog

Fog deposition in tussock grasslands occurs when minute droplets of water in the fog are intercepted by tussock tillers and coalesce to form larger water droplets that fall to the ground. The fine structure of tussock tillers may be conducive to this process by acting as condensation nuclei for droplet formation and coalescence, although condensation will occur on any plant surface when the surface temperature is less than the dew point temperature.

Water derived from fog interception has been shown to be important in a range of ecosystems (e.g., Azevedo and Morgan, 1974; Dawson, 1998; Feild and Dawson, 1998; Corbin *et al.*, 2005). Herckes *et al.* (2002) estimated annual cloud deposition at a high-elevation site (1146 m a.s.l.) in northeastern France at 55 mm, which was approximately 4% of total rainfall. Chang *et al.* (2006) used an empirical model to estimate fog deposition in a mountain forest in northeastern Taiwan and reported 328 mm of fog deposition a year, equivalent to about 10% of the total precipitation. Liu *et al.* (2004) measured fog drip in a seasonal rain forest in southwest China, where fog contributed an estimated 5% of annual rainfall. Research interest in fog has frequently centred on the deposition of dissolved ions in the fog droplets and the link to acid rain. Kobayashi *et al.* (2001) measured deposition of sulphate, nitrate, hydrogen and ammonium ions that was 6–12 times higher in fog than in rain. Kobayashi *et al.* (2001) also point out a common phenomenon in fog interception: the leading-edge effect in which deposition is greatest near a topographic edge, such as a mountain ridge or forest boundary.

The potential importance of fog deposition in the water balance of tussock grasslands was first proposed by Mark and Rowley (1969, 1976) after it was found that tussock tillers mounted in a rain gauge on the Rock and Pillar Range caught water under some conditions when none was recorded in a standard rain gauge. This was then proposed as a mechanism to explain the high water yields found from tussocks in small (0.34 m^2) non-weighing lysimeters. These results were confirmed by Holdsworth (1981), who extended the investigation to the nearby Lammerlaw Range, in upland east Otago. Subsequently, Holdsworth and Mark (1990) used 15 small (0.33 m^2) non-weighing lysimeters and glasshouse trials to investigate snow tussock evaporation rates. The highest water yield came from *in situ* snow-tussock lysimeters, while the transpiration rates from the glasshouse were second highest for snow tussock (after pasture grass). Holdsworth and Mark (1990) subsequently concluded "*interception gains from wind-driven fog (and rain) … may reach c. 120 mm annually at the most fog-prone site.*" As a result Holdsworth and Mark (1990) concluded that the increased water yield from snow tussock compared with other plant covers is only partly related to low transpiration and that fog deposition is an important component of the water balance.

Campbell and Murray (1990) carried out a water-balance study of snow tussock, using a large (5.8 m^2) weighing lysimeter containing an undisturbed soil monolith with nine tussock plants, at Glendhu in the upper Waipori catchment, near Lawrence (Fig. 1). They found high water yields from the tussocks, but an analysis of events where fog could be detected indicated that fog deposition onto snow tussock played only a minor part in the overall water balance (about 1% of total precipitation over an 18-month period). Instead, they attributed the high water yields from tussock grassland to low transpiration rates.

Mark (1998) claimed that the minor role played by fog deposition at Glendhu was not unexpected, given the low frequency of fog at the Glendhu site, which is at a relatively low elevation (570 m). In order to investigate further the role of fog deposition, the large weighing lysimeter used in the Glendhu study was moved, with its 9 tussock plants intact, to a more fog-prone site on Swampy Summit, near Dunedin (Fahey *et al.*, 1996). Over a 3-year period, 40 days were identified as having the potential for fog deposition. Rainfall on these days amounted to 330 mm, but '*apparent fog deposition*' was estimated at less than 2% of the rainfall total for the measurement period (Fahey *et al.*, 1996).

In addition to the lysimeter study of Fahey *et al.* (1996) at Swampy Summit, Cameron *et al.* (1997) investigated the droplet size distribution and liquid water content contained within clouds during a 4-month period. These data were then combined with measured aerodynamic conductance data and used in a water deposition model (Unsworth and Wilshaw, 1989). The model assumes that aerodynamic conductance for cloud droplet deposition is comparable to momentum, and works from basic micro-meteorological principles to derive a deposition rate on a theoretical tussock leaf.

The results showed a difference in droplet size and liquid water content depending on wind direction and that these were similar to those measured elsewhere in comparable environments (Dollard *et al.*, 1983; Fowler *et al.*, 1989). They also showed that water deposition onto tussock during fog events was typically c. 0.05 mm/h, which is in the same order of magnitude as the lysimeter study of Fahey *et al.* (1996). Cameron *et al.* (1997) conclude "*Even the maximum rates predicted would have to prevail for long periods to provide amounts that might influence the runoff from water supply catchments.*"

Ingraham and Mark (2000) used isotopic signatures of water (deuterium and oxygen-18) to identify the origin of water collected as rain, fog and water draining through the soil. The fog collectors comprised a fine-nylon-mesh screen located vertically over a collecting flask and were capped with 1.6 m diameter umbrella-shaped domes to minimise the likelihood of any rain being added to the collector. The rain collectors appeared to be rain gauges mounted close to the ground above collector flasks. The rain and fog collection sites were set up adjacent to places where soil drainage and stream water samples (called 'groundwater') were collected. These were beneath the large weighing lysimeter on Swampy Summit; from a small stream on the Lammerlaw Range; and from a non-weighing lysimeter on the Rock and Pillar Range. Ingraham and Mark (2000) interpreted their results as showing that the water draining through the soil is a mixture of fog and rainwater and therefore it is assumed "*to be a mixture of the two in sub-equal proportions.*" From this they concluded that fog deposition on tussock canopies could substantially augment water yield.

Discussion

The foregoing review shows that there are conflicting views concerning the relative importance of fog deposition versus reduced transpiration in determining runoff from tussock grasslands. Based on the results from 15 small non-weighing lysimeters, Holdsworth and Mark (1990) argue that fog deposition is more important than low transpiration rates, whereas Fahey *et al.* (1996) concluded, from data collected from a single large weighing lysimeter located on Swampy Summit, that less than 2% of total rainfall can be attributed to fog deposition. Using the same lysimeter at Glendhu, Campbell and Murray (1990) also attributed high water yields from tussock grassland to low transpiration, and only 1% of annual precipitation to fog deposition.

Studies of snow tussock transpiration also suggest restricted transpiration is responsible for high water yields from tussock grassland, rather than fog deposition, despite the potential for tussocks to transpire more freely. Snow tussock appears to start controlling its transpiration rate through shutting stomata as the atmospheric demand for water vapour increases (i.e., as the saturation vapour pressure deficit increases). When this is combined with modest wet leaf evaporation, or canopy interception loss (Campbell and Murray, 1990), it is clear that snow tussock is conservative in its use of water. When calculated through the water-balance equation this shows up as a high water yield at both the plant and catchment scale.

Much of the available information on the water balance of tussock grasslands comes from studies involving the use of lysimeters. Because it is normally evaporation (E) that is being estimated with lysimeters, the water balance equation takes the form in equation 1:

$$E = P - Q \pm \Delta S \tag{1}$$

The precipitation (P) is measured in a gauge, or gauges, adjacent to the lysimeter; the percolation (Q) is measured as water exiting the lysimeter at its base; and the change in storage (ΔS) is measured as a weight gain or loss.

Where fog deposition (F) is a factor, the water balance equation of Fahey *et al.* (1996) can be used (equation 2). When the left hand side of equation 2 is positive it can be considered that fog deposition is occurring.

$$(F + E) = \Delta S - P - Q \tag{2}$$

The main criticism of the lysimeter approach is that it is dependent on an accurate measurement of all the variables on the right-hand side of the equation. Of these, it is precipitation that is the most troublesome to measure accurately. It is possible that fog deposition could be overestimated if the rainfall measurement is underestimated and vice versa. This applies to all of the lysimetry studies described here.

Campbell and Murray (1990) presented an error analysis of the weighing lysimeter measurements (table 1, p.234). It clearly showed that the estimates of dry leaf evaporation (transpiration), made during periods of zero or low rainfall, had a low error component, while the estimates of evaporation (or F+E in equation 2) during periods of rainfall were very high. From this we can conclude that weighing lysimeters have a low error component for estimating tussock transpiration rates but are problematic for assessing fog deposition.

In order to minimise the degree of error in measuring rainfall, Fahey *et al.* (1996) used eight rain gauges (including one ground-level gauge) surrounding the lysimeter. However, doubt still remains as to whether the rainfall has been accurately measured. In their definition of fog deposition, Fahey *et al.* (1996, p. 90) state it "*encompasses fog deposition by turbulent transport, but also includes the effects of rain gauge under-catching and we cannot make an explicit distinction in our data.*" By adopting this definition of fog deposition, Fahey *et al.* (1996) are actually accounting for any extra deposition not caught in their rain gauge network, which may or may not be from fog.

Another potential problem with lysimeters is the degree to which the vegetation within the confined tank is representative of natural conditions. Holdsworth and Mark (1990) used much smaller, non-weighing lysimeters, each containing a single tussock. If the tussock is placed above the surrounding canopy, or is isolated, then it will be more prone to catching wind-blown rain or fog than the mixture of plants within a natural canopy. It is well known, for instance, that trees on the edge of a stand intercept more fog and rain than those in the middle; this is referred to as a leading-edge effect (e.g., Kobayashi *et al.*, 2001). In taking measurements it is important to ensure that the lysimeter vegetation represents the canopy, including bare ground between plants, and is not just a single plant. Care was taken in the Holdsworth and Mark (1990) study to ensure the single-tussock lysimeters were surrounded by similar vegetation. However, McSaveney and Whitehouse (1988) point out that, although a single plant may catch fog droplets, it may be causing a fog-drip shadow surrounding it, so that bare ground or the next plant is catching less. This situation is less critical with larger lysimeters such as that used by Campbell and Murray (1990), and Fahey *et al.* (1996). The fact that it was a weighing lysimeter is also important for distinguishing what was occurring during a rain or fog event, rather than treating it as a monthly average of several events.

Ingraham and Mark (2000) used the isotopic signature of stream water and water draining the soil to conclude that the water was derived from a mixture of rain and fog in sub-equal proportions. The authors never clarify what they mean by the term 'sub-equal'. If it is taken to mean 'near to equal' (as defined by Websters Dictionary) then this suggests an amount of fog drip deposition similar to the measured rainfall. As an example, from 21 April 1991 to 29 February 1992, when 1189 mm of rainfall was recorded in the vicinity of the lysimeter on Swampy Summit (Fahey *et al.*, 1996), fog deposition potentially could have contributed another 1000 mm. To achieve fog deposition in amounts similar to rainfall would also require deposition rates over 95% greater than those modelled by Cameron *et al.* (1997). If the isotopic measurements of Ingraham and Mark (2000) were interpreted correctly, then there must be a different fog deposition mechanism than that incorporated into the model of Cameron *et al.* (1997).

There is also the problem of where this extra water from fog could have gone. Water-balance estimates for the tussock catchment at Glendhu show that the average annual rainfall is about 1350 mm, of which 800 mm is converted to runoff, leaving 650 mm to be lost as evaporation (Fahey and Watson, 1991). If fog and rainfall occur in sub-equal amounts, then the total precipitation figure could be as high as 2800 mm. Working through the water balance equation, the extra 1450 mm of water must be absorbed through a 100% error in both the measurement of streamflow and estimation of evaporation. This would be an unreasonably high degree of error for a catchment experiment.

Fog, being generated close to the ground surface and at an early stage of condensation, has a higher proportion of heavy isotopes than rain, which is generated higher in the atmosphere (Ingraham and Mark, 2000). Ingraham and Matthews (1988) proposed that where groundwater samples show a greater ratio of heavy isotopes, it could be used as an indicator of fog contribution to the groundwater. The data from Ingraham and Mark (2000) show that the isotopic signature of water draining through the soil profile (labelled groundwater) falls somewhere between the signatures of water collected in the horizontal and the vertical plane (labelled as rain and fog respectively). This is interpreted as indicating that the groundwater must contain sub-equal parts of fog and rainfall. There are two other equally plausible explanations for this result: 1) enrichment of the isotope ratio through evaporation and/or isotopic exchange, and/or 2) the water was resident in the soil profile for longer than the rainfall collection period.

As water evaporates, the remaining water becomes progressively enriched in deuterium and oxygen-18 (Stewart, 1975). In drier conditions, this leads to a characteristic ratio between the enrichments of about 4, allowing evaporation to be recognised from its isotopic effects. However in humid conditions (such as in the Otago uplands), the process involves more rapid exchange with the atmospheric vapour, and the ratio becomes steeper (near 8) and therefore indistinguishable from mixing processes. While it is clear from the methodology of Ingraham and Mark (2000) that evaporation did not occur after collection of water at the base of the lysimeters (oil was placed in the sample collectors to prevent evaporation), it will have occurred while water moved from tussock leaf to the base of the lysimeter (through wet leaf evaporation and bare-soil evaporation). The evaporation explanation is dismissed as "*unlikely … given the relatively low rates of evapotranspiration from snow tussock land on the Otago uplands*" (Ingraham and Mark, 2000, p. 406). While it is true that evapotranspiration rates are relatively low (compared with pasture), they are still significant. For example, annual wet canopy evaporation from the tussock plants in the weighing lysimeter at Glendhu was 21% of total precipitation—approximately 300 mm (Campbell and Murray, 1990). Wet canopy evaporation can also take place during rainfalls and possibly even at night (Pearce *et al.*, 1984). Water collected in the rain gauges will have had no evaporation enriching the isotopes. Water that lands on the tussock will have evaporation enrichment and therefore the water entering the soil will also be more enriched. Corbin *et al.* (2005) use the same isotopes as Ingraham and Mark (2000) to distinguish the water used by plants that is derived from fog and that derived from stored rainfall. Corbin *et al.* (2005), however, were able to make a specific correction in the isotopic analysis to account for evaporation from the soil because of their much drier conditions and therefore the characteristic isotopic enrichments due to evaporation. In the results of Ingraham and Mark (2000) enrichment of isotopes through evaporation could explain the isotopic signature for water draining from the base of the lysimeters equally well as the water being a mixture of fog and rainfall.

In coming to the conclusion that sub-equal proportions of water draining from the soil were derived from fog and rain, the actual volumes of water collected in the horizontal and vertical planes during the period of study were never specified. It would be interesting to know this information so that a mass-balance calculation could be used to test the concept of sub-equal proportions. This would go some way to deciding whether enrichment of isotopes through evaporation may be a more plausible explanation for the results.

An alternative explanation for the results of Ingraham and Mark (2000) can be found in the time taken for water to move through the soil profile. In coming to their conclusion of '*sub-equal parts*', the authors make the critical assumption that the '*lag time is negligible*' (p. 405) in water moving through the soil profile. This is based on the observation of Holdsworth and Mark (1990) that soil moisture seldom gets below field capacity. What is important for their interpretation is that the water collected at the bottom of the lysimeters, or the stream at Lammerlaw, is from the same storm events as the water collected in the vertical and horizontal collectors. This is clearly unlikely—i.e., the soil water would have been recharged before the fog and rain was collected. The water that was collected at the base of the lysimeter (and stream) was most likely old water pushed out the bottom as piston flow as the rainfall infiltrates at the surface. Lindstrom and Rodhe (1992) found the residence time of water travelling through 80 cm deep lysimeters was between 3 and 6 months (average of 4 months) and that the piston flow mechanism predominated at greater depths. It is impossible to test the assumption of negligible lag time made by Ingraham and Mark (2000), without information on soil water properties, volumes of water infiltrating, and the sample collection period; these are not presented.

The observation is also made "*that the groundwater also displays less fluctuation in isotopic compositions than the rain or fog*" (Ingraham and Mark, 2000, p. 406). It is common hydrological practice to compare the fluctuations between rainfall and groundwater isotopic time series (e.g., Bonell *et al.*, 1990). This technique is used to estimate the soil or groundwater residence time (Genereux and Hooper, 1998). The observation of Ingraham and Mark (2000) that there is less fluctuation in the groundwater signal could be interpreted to mean the water has been resident in the soil for several months. The dampening down of the fluctuation occurs through mixing of different rain waters in the soil over a period of time. To test this fully would require information on the residence time distribution of sampled groundwater.

A question arising out of the conclusions of Ingraham and Mark (2000) is whether there is any evidence from the catchment studies in the east Otago uplands that fog deposition adds to water yield. Duncan and Thomas (2004) found that the majority of change in water yield following burning of tussocks at Elbow Creek in the Lammermoor Range occurred through a reduction in peak flows. There was no detectable change in low flows following burning. A decrease in fog deposition is a possible cause for the observed decrease in flows, but Duncan and Thomas (2004) dismiss this on two counts. First, the main change in flows occurred after 2 years, whereas the loss of tussock tillers, and therefore the ability to intercept fog, was immediate. Secondly, they point out that if fog interception is important, any reduction would be reflected in the low flows rather than peak flows, whereas in the Deep Creek study the reverse was true.

There are strong similarities in the summer flow regimes (November to April) for Elbow Creek in the Lammermoors and for the Glendhu tussock catchment in the upper Waipori basin. Over the 13 summers of concurrent flow and rainfall data for the two catchments (1980/81 to 1992/93), 57% of rainfall was converted to runoff in Elbow Creek and 54% at Glendhu. Since the incidence of fog is likely to increase with elevation, if it is capable of substantially augmenting water yields from tussock grasslands, then we would expect the percentage of rainfall converted to flow to be much lower at Elbow Creek (elevation 1000 m) compared with Glendhu (elevation 550 m), when in fact the reverse is the case.

One final question needs to be answered. Does it really matter to resource managers whether the high water yields from a tussock land cover are a result of reduced transpiration rate or fog interception? All the studies agree that tall tussock has a high water yield compared with pasture and trees. Therefore maintaining tussock grasslands is sensible from a water resource perspective. However, if we apply the fog interception results to other parts of the South Island high country where there are significant areas of tall tussock but little fog, it would be hard to argue for preservation of the tussock on the basis of water yield alone. If, however, the causal mechanism is reduced transpiration, then the same mechanism would occur wherever tussock grasslands are found, and it would be worth preserving them for both water and conservation values.

Conclusions

From the above discussion, we conclude that tussock grasslands sustain high water yields in the uplands of east Otago through reduced transpiration rather than from fog deposition. The lysimeter results are admittedly inconclusive on this issue. Measurements from small non-weighing lysimeters suggest that fog deposition is an important contributor, whereas the results from the large weighing lysimeter suggest just the opposite. Inaccuracies in the measurement of fog deposition are likely with both types of lysimeters because of the inherent error component of rainfall measurement. These become critical when measurements are infrequent, as was the case with the non-weighing variety lysimeter, necessitating a reliance on monthly averaging to reach conclusions about the relative contributions of the various components of the water balance. Edge effects are likewise difficult to avoid with small lysimeters that contain single tussock plants.

The paper by Ingraham and Mark (2000) adds to the debate over the importance of fog deposition through the introduction of a different methodology to lysimetry. However there are other, equally valid, explanations for the same results that do not lead to the conclusion that fog deposition makes a substantial contribution to water yield.

The results from tussock transpiration studies, micrometeorological modelling, and catchment water-balance investigations all point to reduced transpiration during dry periods, rather than fog deposition, as the most likely mechanism responsible for augmenting water yield from tussock grassland.

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