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Fog deposition by snow tussock grassland on the Otago uplands: response to a recent review of the evidence

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Abstract
We challenge a recent, rather selective 'review of the evidence' by Davie *et al.* (2006) explaining the recorded high water yields from snow tussock grasslands on the Otago uplands. We refute their dismissal of the importance to water yield of fog deposition on the fine wispy foliage of the dominant tall tussock plant cover. We stand by the results of our previous study on the stable isotope ($\delta^{18}O$ and $\delta^{2}H$) values of fog-, rain- and groundwater from three upland snow tussock grassland sites. We also provide evidence from several direct measures using natural or simulated tussocks at three fog-prone upland locations which the reviewers ignored. Overall and importantly, the value of upland snow tussock grassland in maximising water yield is not in dispute, and we continue to endorse the relevance of low evapo-transpiration from the dominant tussock cover. The water production capability of the upland snow tussock grasslands is a sufficiently important ecosystem service to justify formal recognition in land-use planning responsibilities of local authorities. Further, this important ecosystem service of upland tall snow tussock grasslands should also feature in central government's current Sustainable Water Programme of Action and in the development of National Policy Statement and National Environmental Standard for water under the Resource Management Act.

Keywords
Fog deposition, stable isotope analyses, evapo-transpiration, interception gain, upland snow tussock grassland, water yield, ecosystem service.

The issues
The high water yield from snow tussock grasslands, relative to yields from alternative types of cover on the Otago uplands, measured by several researchers in different locations and using a range of methods, is an important and undisputed ecosystem service, with relevance to land-use planning. A recent 'review of the evidence' explaining the consistently high water yields measured from these upland grasslands (Davie *et al.*, 2006) dismisses one of two major hypotheses proposed to account for these high yields, that is the significant fog deposition gains made by the fine wispy foliage of the dominant tall tussock grasses. Instead, these authors attribute the recorded high water yields to relatively low evapo-transpiration from these dominant snow tussock grasses. Not only is the information presented by the critics highly selective, but the case they make in dismissing the evidence from a stable isotope

study of the importance of fog deposition gains to water yield (Ingraham and Mark, 2000) is fundamentally flawed.

Davie *et al.* (2006) claim there are 'two camps' providing explanations for the high water yields from these upland grasslands, one which supports low evapo-transpiration of the dominant snow tussocks and the second invoking significant gains of water from fog deposition on the snow tussock canopies. This either/or assertion is incorrect, as those proposing gains from fog water deposition have also given credence to low evapo-transpiration, as the following three quotations indicate:

1) 'The increased water yield associated with snow tussock grassland is only partly related to its relatively low AE [Actual Evapo-transpiration] values. It also reflects interception gains [deposition] from wind-driven fog (and rain) by the tall caespitose habit and linear leaves of the dominant tussocks' (Holdsworth and Mark, 1990; Abstract);
2) the 'significantly greater yields of water .. from …*Chionochloa* grassland than from a range of modified types … is because of relatively low transpiration rates of *Chionochloa*, combined with interception gains [deposition] from frequent fog and light rain … by the tall, fine foliage of the *Chionochloa* spp.' (Mark, 1993; p. 400); and
3) 'given the relatively low rates of evapo-transpiration from the snow tussock grasslands on the Otago uplands ….' (Ingraham and Mark, 2000; p.406).

Indeed, it was the research by one of us (AFM) that established the low evapo-transpiration rates of *Chionochloa rigida* and its significance with respect to water yield (Mark, 1975). There is now a considerable body of work that confirms the importance of low evapo-transpiration of the dominant snow tussock species, *Chionochloa rigida*, involving whole catchments (Pearce *et al.,* 1984; Duncan and Thomas, 2004), weighing (Campbell, 1987, 1989**;** Campbell and Murray, 1990; Fahey *et al.*, 1996) and non-weighing (Mark and Rowley, 1976; Holdsworth and Mark, 1990) lysimeters, plus direct measurements (Mark *et al.*, 1980; Espie and Grau, 1994, 1995; Mark, 1998) and eco-physiological aspects (Mark, 1975; Pollock, 1979).

Three major issues are in dispute: fog deposition (interception gains) by the tussock canopy, aspects of the isotopic analyses made by Ingraham and Mark (2000), and discharge rates and age of the lysimeter/groundwater they sampled. These issues will be dealt with in turn, followed by additional relevant published information that was not discussed by the critics.

Interception: losses and gains

The term interception describes the moisture which is caught and stored on the leaves and stems of plants. Interception loss, which occurs through evaporation of water from damp vegetation, is well documented as a valid component of a water balance. However, the ability of vegetation to intercept wind-driven fog droplets that contribute to the water input through fog deposition is less generally accepted, as such a function relates to regional climate. Such fog deposition (or 'interception gains') might be considered as stemflow and/or throughfall, technical terms which generally refer to the dispersal of rain-water in woody vegetation. It has also been referred to as interception gain (Mark and Rowley, 1976; Holdsworth and Mark, 1990; Mark, 1998) or fog deposition (Ingraham and Mark, 2000) and we will continue with the preferred latter term in this paper.

There is a continuum of droplet sizes between fog and rain, and we accept Fahey *et al.*'s (1996) definition of fog in this context, that it is 'any liquid water which collects on a tussock canopy but is not caught in a rain gauge' and further, that 'fog water droplets are generally smaller than 20 μm diameter while the conventional size separation between fog and rain droplets is 100 μm diameter'. Water derived from fog deposition on vegetation has been shown to be important in a wide range of ecosystems outside New Zealand, a point freely acknowledged by Davie *et al.* (2006). For instance, the significance of fog has been documented in Australia (Costin and Wimbush, 1961; Edwards, 1973), coastal California (Azevedo and Morgan, 1974; Ingraham and Matthews, 1988b, 1990, 1995; Dawson, 1998; Corbin *et al.*, 2005), and in tropical and subtropical montane cloud forests (Weaver, 1972; Zadroga, 1981; Bruijnzeel and Proctor, 1995; Juvik and Nullet, 1995; Hutley *et al.*, 1997; Holder, 1998; Field and Dawson, 1998; Bruijnzeel, 2001), as well as other mountain regions including Taiwan (Chang *et al.*, 2006), China (Liu *et al.*, 2004), Mexico (Vogelmann, 1973), the Andes (Biederwieden *et al.*, 2005; Buytaert *et al.*, 2006), Chile (Ingraham and Cereceda, 2001), East Africa (Ingraham and Matthews, 1988a) and the French Alps (Herckes *et al.*, 2002). Moreover, fog deposition with specially built structures can provide significant amounts of water for various human uses (Schemenauer and Cereceda, 1994). Such structures are used, particularly in arid and semi-arid coastal (Schemenauer and Cereceda, 1991; Jaén, 2002) and/or mountain (Schemenauer and Cereceda, 1992; Olivier and Rautenbach, 2002) locations in many regions of the world.

Given this world-wide understanding, it is puzzling that the significance claimed for fog deposition in contributing to water yield on fog-prone uplands in New Zealand has been challenged (McSaveney and Whitehouse, 1988; Davie, *et al.*, 2006). The contribution of water from fog deposition on vegetation to a site's water yield has generated controversy in New Zealand since it was first proposed by Rowley (1970), even though its importance is accepted elsewhere in the world. Studies of the ecological significance of fog, and particularly gains of water through fog deposition, have mostly involved forested regions and have been widely accepted. Grasslands and other indigenous non-forest ecosystems have received much less attention and, given their lower stature and often smoother canopies, might be expected to be much less efficient in intercepting wind-driven fog, even in fog-prone regions. Grasslands are not homogeneous in structure or composition, and it is the tall tussock life form that is particularly significant for fog deposition in New Zealand and elsewhere.

Such a life form also prevails in the alpine páramo tall tussock grasslands of the northern Andean highlands. Buytaert *et al.* (2006) describe the páramo as 'the major water provider for the Andean highlands of Venezuela, Colombia and Ecuador, extensive parts of the adjacent lowlands, and the coastal plains of North Peru. The water quality is excellent, and the rivers descending from the páramo provide a high and sustained base flow.' Also relevant are the comments: 'While the total amount of rainfall is not particularly high in most páramos, the region is known as very cold and wet, because it is almost continuously covered with fog and drizzle.… The water balance of the páramo is subject to large uncertainties. In particular, the role of the natural páramo vegetation in the water cycle is unknown. This role extends beyond water consumption, as evidence and observations suggest that interception and microclimate regulation may be important as well.' According to Buytaert *et al.* (2006) water production from a series of small catchments in Ecuador was found to range from 600 to 1000 mm yr^{-1}, or about two-thirds of the annual rainfall, while conversion of the natural grass vegetation to either cultivation or *Pinus radiata* reduced water yield from natural catchments, by up to 70% for a *Pinus* catchment. This is generally consistent with the situation recorded for the Otago uplands.

The dominant snow tussock cover on the Otago uplands is ideally suited for fog deposition in terms of its fine wispy and aerated foliage, and the associated high above-ground biomass (Mark, 1993). The earlier 'review of the evidence' by McSaveney and Whitehouse (1988) attributed the relatively high runoff and sustained moderate flows in these upland regions to low evapo-transpiration losses and the presence of 'many bogs and ponds, and the widespread coarse debris mantle' but did admit that snow tussock grasses do collect water from fog. They claimed, however, that 'the amounts appear to be very small' and that much more is collected from wind-driven rain since 'all of the rain and probably much of the fog would fall on the ground if not first caught on tussocks.' We accept the importance of low evapo-transpiration and also the case made for rain. However, we reject the comment on fog since, in the uplands it is associated with often fast-moving air masses and may dissipate beyond the mountain mass, or be at a higher elevation, as described by Cameron *et al,* (1997). Relatively few of the fog droplets appear to fall directly on the ground and the water retained on the tussock foliage runs down the snow tussocks' furrowed leaves during a heavy fog, even in the absence of obvious accompanying rain (Fig. 1).

Figure 1 – Water droplets intercepted from fog on the fine foliage of narrow-leaved snow tussock, *Chionochloa rigida*.

Isotopic analyses

Davie *et al.* (2006) criticised the study by Ingraham and Mark (2000), who collected lysimeter/groundwater samples concurrently with rain- and fog-water from three snow tussock grassland sites on the Otago uplands over two snow-free periods. The rain-water was consistently more depleted in the stable heavy isotopes of oxygen (^{18}O) and hydrogen (D) than the fog, while the groundwater had compositions usually between those of the fog and rain samples (see Figs. 2 and 3). These results were interpreted as the groundwater being a mixture of the two 'in sub-equal proportions'. Ingraham and Mark (2000) therefore proposed that interception gains through fog deposition on the foliage of the dominant snow tussock cover make a 'substantial contribution to the water yield from these uplands'.

Davie *et al.* (2006), however, have two major criticisms of the stable isotope data presented by Ingraham and Mark (2000) and offer 'two other equally plausible explanations' for the groundwater results: '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.' Each of these is addressed below.

Stable isotopes and the effects of evaporation

Regarding criticism of the interpretation of the isotopic composition of the lysimeter/ groundwater by Davie *et al.* (2006), they are correct in their statement that the process of evaporation will cause a water to become more enriched in its stable isotopic composition.

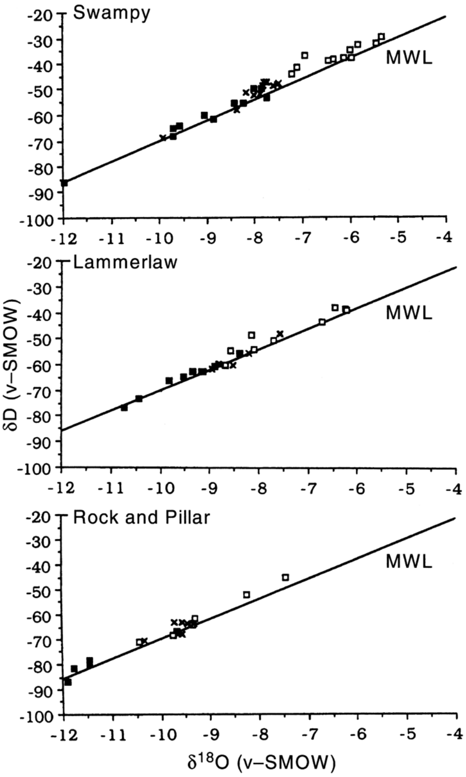

Figure 2 – Stable isotope (δ18O and δD) composition of the fog (□), rain (■) and lysimeter/ground-water (x) samples collected at each of three sites on the Otago uplands: Swampy Summit (736 m. a.s.l.), Lammerlaw Range (870 m) and Rock and Pillar Range (1140 m), are shown with the meteoric water line (MWL). Reproduced, with permission, from Ingraham and Mark (2000).

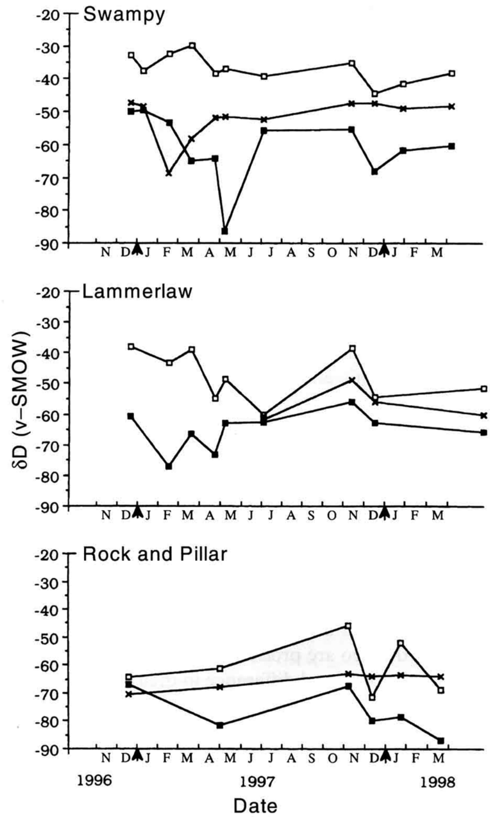

Figure 3 – The time series of the δD values of the fog (□), rain (■) and lysimeter/ground-water (x) samples collected at (top) the Swampy Summit site; (middle) the Lammerlaw Range site and (bottom) the Rock and Pillar site. The δD values of the contemporaneous rain and fog vary through time but fluctuate in unison. The groundwater fluctuates less and only appears to parallel the rain and fog at the Lammerlaw site. However, at all three locations, the groundwater commonly has a composition between that of fog and rain, and probably is a mixture of the two in subequal proportions. Reproduced, with permission, from Ingraham and Mark (2000).

They also state that enrichment by evaporation would produce a characteristic δD–δ^{18}O slope of about 4. Equilibrium fractionation is accompanied by an additional kinetic fractionation during evaporation. The value of the kinetic addition is mostly dependent on the relative humidity during evaporation and, at any given relative humidity, the additional kinetic factor is near equal for both hydrogen and oxygen (Stewart, 1975). However, the kinetic addition affects the oxygen isotopic ratios commensurably more, since the equilibrium fractionation factor for oxygen is about 12% that of hydrogen. Gonfiantini (1986) gives the mathematical basis for this relationship. At low humidity, the kinetic addition is greater and the remaining water will plot on a δD–δ^{18}O slope of less than 4.

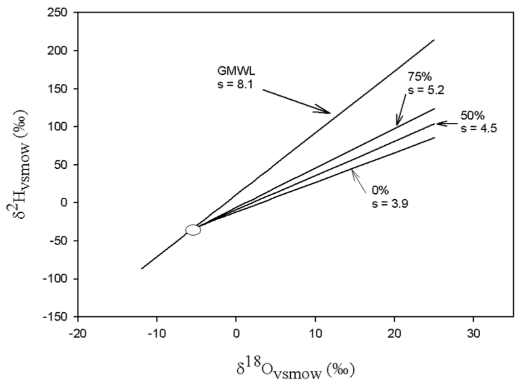

Figure 4 – Isotopic enrichment of evaporating water and the effect of humidity. The slopes are approximations from Gonfiantini (1986) of the early portion of each curve for waters evaporating under the different relative humidities. Note the regression line for the meteoric water line (MWL) of near 8 is reduced by evaporation to near 4.

At higher relative humidities the remaining water will plot on a δD–δ18O slope of greater than 4, perhaps as high as 7; depending on the relative humidity (see Fig. 4). The slope of 4 proposed by Davie *et al.* (2006) is simply an arbitrary chosen value of the resultant kinetic enrichment along the continuum (Ingraham, 1998; Ingraham *et al.*, 1998; Kendall and Caldwell, 1998). Davie *et al.* (2006) themselves acknowledge that all of the data presented in Ingraham and Mark (2000) plot along a slope of 8 and not along a slope of 4. In fact, the specific samples that would be required to partake in evaporation (rain and lysimeter) plot along a slope of 8.15. Thus, the stable isotopic compositions simply do not display the isotopic effects of evaporation under ambient relative humidities, which previous records indicate are generally high at all three sites (see Holdsworth and Mark, 1990; Fahey *et al.*, 1996). To argue that a shift in the isotopic composition along a slope of 8 was the result of evaporation would require an extreme loss of water by evaporation during a very short period of time under relatively high humidity. These conditions are simply mutually exclusive. Moreover, the isotopic composition of the soil water is not affected by the transfer of water from the soil to the plant. That is, plant roots cannot discriminate between the heavy and light isotope (White *et al.*, 1985; Ingraham *et al.*, 1993). Only in the foliage, where transpiration occurs, can the isotopic compositions be affected.

Davie *et al.* (2006) refer to a study of summer water use by coastal prairie grasses in California by Corbin *et al.* (2005) who 'were able to make a specific correction in the isotopic analysis to account for evaporation from the soil because of the much drier conditions and therefore the characteristic isotopic enrichment due to evaporation'. Davie *et al.* (2006) are correct in stating that coastal California has 'much drier conditions' than the Otago uplands in southern New Zealand. Had the characteristic enrichments due to evaporation been observed by Ingraham and Mark (2000), a specific correction in the isotopic analysis to account for it could also have been made. However, as Davie *et al.* (2006) state, such an isotopic enrichment was not observed.

The study by Corbin *et al.* (2005) of water relations in coastal prairie grasses in northern California, although apparently not involving measurements of the amount of moisture deposited from fog, did use the same stable isotopic method as Ingraham and Mark (2000) and obtained ratios for water from several perennial grass species and the soil. Their results indicated that 28–66% of the water taken up by the plants during summer was sourced as fog rather than residual soil water from winter rain. One of the co-authors of this study, Dr T. Dawson (pers. comm., 2007), commented that 'these grasses do intercept the fog directly. These are advection fogs that move each evening off the Pacific Ocean and 'through' the vegetation of grasses, shrubs and redwood trees. Then early in the morning as the fog dissipates we see a marked 'evaporation effect' as evidenced by the evaporation regression we highlight in the 2005 paper.'

As Davie *et al.* (2006) explain, Corbin *et al.* (2005) made a specific correction in the isotope analysis to allow for evaporation from the soil, and they also claim that similar evaporative enrichment could have explained the results of Ingraham and Mark (2000) for their lysimeter/groundwater samples. We reject this criticism by Davie *et al.* (2006), given that the isotope ratios for all of the lysimeter/groundwater samples were close to the meteoric water line and not on evaporation lines resulting from isotopic enrichment, as recorded by Corbin *et al.* (2005). Moreover, Ingraham and Mark (2000) showed that the timing of the fog and rain depositions was immaterial to the current argument since, as expected, their rain and fog samples fluctuated isotopically at all sites, representing variations in the weather patterns at the time (Fig. 3). This figure shows the lysimeter/groundwater values, on average, balanced between them (hence 'sub-equal') and showed considerably less fluctuation as it was more homogenised through time (Fig. 3).

Discharge rates and the age of groundwater

Another concern of Davie *et al.* (2006) relates to the time taken for water to move through the soil profile. Indeed, they indicate that the interpretation by Ingraham and Mark (2000) of the lysimeter/groundwater they analysed was unlikely to have been from the same storm events as the water collected as rain and fog. Rather, they claim that this water 'was most likely old water pushed out the bottom as piston flow as the rainfall infiltrates at the surface.' We accept this interpretation but note that 'old' water is not defined and, moreover, they refer to a residence time of 3 to 6 months (average 4 months) for lysimeters of 80 cm depth, admitting 'that the piston flow mechanism predominated at greater depths' (note, the lysimeters used by Ingraham and Mark were <80 cm deep). Assuming the lysimeter drainage water analysed by Ingraham and Mark (2000) was no older than 6 months (the isotope ratios obtained for the water from the small (first-order) stream at their Lammerlaw site indicates that all such samples were of generally similar age). These would likely be equivalent to the ' "new" water from saturated overland flow' as opposed to the 'old' water in the context of that 'from a shallow, unconfined groundwater reservoir' measured by Bonell *et al.* (1990) from the Glendhu catchment.

Assuming the soil water is a partially homogenized mixture of rain and fog, we question why the actual age of the water is relevant. We assume small amounts of fog-water would be frequently admixed into the system, while rain would occasionally add measurable amounts of water that would mix with existing water in the soil. If the soil water is not at field capacity there would be none draining out and the rain and fog would mix and become more homogenized, whereas if at field capacity, as we assume it was, the rain-water could create a pressure pulse and push the lower water out below and replace it in the soil. A possible hystoresis effect may be an issue but the age of the water should be irrelevant; it is still a mix of rain and fog.

Davie *et al.* (2006) suggest that the isotopic values recorded in the lysimeter/groundwater could have been the result of isotopic exchange. This shift would require an enrichment in δD of about 10 per mil, and 1 per mil in $\delta^{18}O$. Shifts in stable isotopic composition by exchange are possible if two waters are in vapour communication in a closed system (Ingraham and Criss, 1993, 1998). Under these conditions, the degree to which the waters can shift may be calculated, based on their mass balances. Davie *et al.* (2006) do not suggest any water in the proximity that might partake in this process. However, there is a water in the proximity with an isotopic composition sufficiently enriched that could produce the observed values in the lysimeter/groundwater. That is the water derived from fog. By whatever method, isotopic exchange or direct mixture, fog-water appears to be important in explaining the observed stable isotopic composition of the lysimeter/groundwater recorded by Ingraham and Mark (2000).

Comments on scientific, semantic and isotopic criticism

Stable isotope analysis allows differentiation of various sources of water (Ingraham and Matthews, 1988a, 1988b, 1990, 1995; Ingraham, Matthews and Casas, 1993; Ingraham and Cereceda, 2001). It is a powerful technique which surmounts the difficulty of designing a fog collector that has the direct collection capabilities of a tussock leaf. Nevertheless, knowing the general wind strength in the region, serious consideration was given to collecting separate samples of fog- and rain-water, as described by Ingraham and Mark (2000). However, the actual volumes of water collected were not specified, given the difficulty of accurately measuring the amount of rain reaching the ground beneath a tussock, and considering the possibility of interception, throughfall and stemflow. Davie *et al.* (2006) had no criticism of the methods used to collect the rain and fog samples, and thus the stable isotopic compositions of these samples apparently are not in question.

Regarding semantic criticism, the term 'sub-equal' was used by Ingraham and Mark (2000) to indicate the relative contributions of fog and rain present in the lysimeter/groundwater as recorded by the stable isotope data. This term appeared to confuse Davie *et al.* (2006) who state (p. 89), 'the authors never clarify what they mean by the term sub-equal' but this can be readily determined by perusal of the hard data. Ingraham and Mark (2000) took a conservative approach when reporting the results. The actual proportions of fog- and rain-water were not quantified in the paper to preclude any incorrect interpretations. Published percentages tend to take on a life of their own and, while we believe the contribution of fog-water is significant as identified by the stable isotope values for the lysimeter/groundwater, there are minor factors controlling these actual values other than the direct influence of rain and fog. Moreover, there was no way to accurately determine the relative proportions of rain- and fog-water collected to calculate an accurate mass balance. We considered that readers of the paper would peruse the data as well as read the prose. As such, they could make their own judgments concerning the relative proportions of the isotopic compositions of rain and fog needed to produce that recorded in the lysimeter/groundwater, since delta (δ) units are conservative. However, since it appears that Davie *et al.* (2006) were confused by the data and the word 'sub-equal', we have calculated from the raw data the ratio of fog and rain that would need to be mixed in order to obtain the isotopic composition recorded for the lysimeter/groundwater (not an accurate mass balance). The Lammerlaw site would require 47% fog- and 53% rain-water, the Swampy Summit site 37% fog- and 63% rain-water, and the Rock and Pillar site 65% fog- and 35% rain-water. The sum total of all three sites (again not considering strict mass balance calculations) would require 49.6% fog- and 50.4% rain-water; that is sub-equal or near-equal amounts of each in the lysimeter/groundwater samples.

Additional information

There is also a considerable amount of relevant information obtained since the mid 1960s from the Central and eastern Otago uplands, which lends credence to the likely importance of interception gains from fog deposition in contributing to water yield, although this research was not discussed by Davie *et al.* (2006). The initial attempt to record fog deposition with the first study (Rock and Pillar Range, 1000 m) used 32 mature snow tussock tillers mounted on a coarse wire mesh inside the rim of a standard rain gauge, and a similar arrangement with tillers clipped to 20 cm. Both were placed adjacent to a standard rain gauge. This set-up, which was repeated near the summit of Mt Cargill (676 m; a coastal fog-prone site near Dunedin), clearly indicated the importance of fog deposition by snow tussock leaves to gain water from wind-driven fog (Rowley, 1970). This was later confirmed at the Rock and Pillar site with the addition of a Grunow fog catcher, and using three recording gauges (Mark and Rowley, 1976; Mark *et al.*, 1980).

The problem of over-exposure inherent in these early studies was later corrected. Twelve whole snow tussocks were transplanted to the Mt Cargill site and, with soil and most roots removed, mounted singly over a wire mesh frame in 10 litre polythene buckets which were buried to their rims and spaced 3 m apart in a line perpendicular to the prevailing fog-bearing northeasterly wind. The tussocks were deployed only during days with fog (observable from the base in Dunedin); otherwise they were cached together in a moist depression. Up to 0.5 litres per hour of water was deposited on individual tussocks from dense fog during periods with negligible recordable rain. Moreover, increasing tussock density up to 5 m^{-2} (note: 3–4 m^{-2} occur in intact snow tussock stands: see Rowley, 1970), with additional plantings showed that, although the catch per tussock declined as tussock density increased, catch per unit area (equivalent to *c.* 0.5 mm h^{-1}) did not (see Mark *et al.*, 1980; Fig. 9).

A later fog deposition study at 1100 m in the upper Deep Creek catchment on the Lammermoor Range, eastern Otago,

Figure 5 – The fog interception set-up at 1100 m in the upper Deep Creek catchment, showing the 40 snow tussock tillers from the site, mounted on a recording rain gauge (lower centre) among otherwise undisturbed narrow-leaved snow tussock grassland.

associated with a lysimeter study here (see below), used a simulated snow tussock (40 mature tillers coated in silicone to hold them erect in a coarse wire mesh), mounted at canopy level on a recording rain gauge within an area of intact grassland (Fig. 5). Results confirmed the importance of fog deposition gains during the frequent periods of fog (Mark, 1998). Here a recording rain gauge, monitored hourly with a data logger over two snow-free (Nov.-April, 1988–90) periods, together with humidity, wind speed and direction, solar radiation, air and soil temperatures, indicated that fog occurred on *c.* 29% of the 306-day recording period. Most fogs were associated with cold fronts from the west-southwest and were separated into 'light' and 'heavy' on the basis of the rain gauge catch. Light fogs (defined as periods with saturated air when the standard rain gauge recorded <0.1 mm h^{-1}), contributed 50% of the recorded fog events and lasted 61% of the time when fog occurred. During these times, the simulated tussock deposited 1.54–4.00 mm h^{-1} of water. This result was equivalent to a total of 123 mm of water input to a unit area of ground during the study. Heavy fogs (defined as saturation events which deposited 0.1–1.0 mm h^{-1} of rain), were less common but represented 35% of the fog events and 30% of the fog duration period. These events contributed 154 mm of deposited water over the 306-day study period. Rain events (defined as contributing >1 mm h^{-1}, with or without fog, were excluded from the analysis. Therefore, the water derived from fog deposition by the simulated tussock over the recording period (277 mm over 306 days) would represent 166 mm input over a 6-month snow-free period. Put another way, it would provide a 22% addition to the mean precipitation recorded with a standard rain gauge for the same 6-month period at this site (755 mm) over the 4-year period of measurement (Mark, 1998) and, as explained, this is likely to be a minimal value.

Results from a 4-year lysimeter study (1988-92) in the same upper Deep Creek and nearby Elbow Stream catchments at 900–1120 m (Mark, 1998) are also relevant, particularly in relation to a concurrent paired catchment study here. The latter began in 1980 (Duncan and Thomas, 2004) and Davie *et al.* (2006) refer to this study in relation to the water yield responses following the burning of 70-80% of the Deep Creek catchment in September 1988. The burned catchment showed reduced yields of water during the first three years (consistent with prior lysimeter results from the Rock and Pillar Range by Mark and Rowley, 1976). This result was interpreted by Duncan and Thomas (2004) as being due to increased transpiration by the new foliage and 'greater loss of intercepted moisture because of increased air circulation through the less dense tussock canopy.' The statement that 'summer low flows were barely changed by burning the tussock' was interpreted by Duncan and Thomas (2004) and by Davie *et al.* (2006) to be unrelated to 'a decrease in fog deposition' even though Duncan and Thomas (2004) also state that 'the mean trend was for most months in 1989 to 1991 (the post-burn period) to have … smaller flows than would have been expected'. The lysimeter study described by (Mark, 1998) was located in the upper reaches of both these catchments, using duplicate tanks, set up as in the Holdsworth and Mark (1990) study, with three cover types: bare soil, blue tussock and snow tussock (those in the burnt Deep Stream catchment were also burned). Operated for four years following the fire, there was little difference between the two catchments in mean yields from the lysimeters over the four snow-free periods from bare soil (43 and 45%) and the short blue tussock (*Poa colensoi*) grassland (both 56%). The snow tussock grassland, however, yielded 92% of the 622 mm precipitation with little yearly variation from the unburned tall snow tussock grassland in the Elbow Stream catchment, but with the burned tussock grassland in Deep Creek the yield increased steadily as the tussocks recovered their canopies, from 62% in the summer following the fire to 84% four years later (Mark, 1998). Neither these results nor those for the substantial fog deposition gains recorded from the upper Deep Creek catchment were discussed by Davie *et al.* (2006) even though they referenced this paper.

Davie *et al.* (2006), however, do refer to the study of Cameron *et al.* (1997) which attempted to estimate fog deposition in the tall tussock grassland at the Swampy Summit study site used by Ingraham and Mark (2000). Cameron *et al.* (1997) examined fog droplet size and density with a forward scattering spectrometer probe placed about 1.0 m above the tussock canopy, which was 80 cm tall, with a one-sided leaf area index of 3.0. They also measured horizontal and vertical wind speeds at 3.5 m above the canopy over four summer months. Deposition rates of 0.02–0.26 mm h^{-1} (mean 0.05 mm h^{-1}) of water were recorded, based on their fog deposition model. These results showed the contribution of fog represented 20% of the average rainfall rate for the same period. Notwithstanding, they concluded that such interception gains were unlikely to be a significant component of the water balance of a tall tussock grassland catchment.

Value and limitations of lysimeters

As discussed by Holdsworth and Mark (1990), similar water balance results were obtained with snow tussock grassland on the Otago uplands from Mark and Rowley's initial study using small non-weighing lysimeters containing a unit area of snow tussock grassland, and from the catchment study by Pearce *et al.* (1984), as well as the one-year weighing lysimeter study at Glendhu by Campbell (1987). We remain confident that the lysimeter approach is capable of providing reliable information on water yields, despite some early criticisms (Gillies, 1978; McSaveney and Whitehouse, 1988).

As Holdsworth and Mark (1990; p. 2) stated, 'reliable measurements of water yield in the South Island high country pose problems with the logistics of equipment operation and servicing, and in locating areas which meet the requirements of both water-tight and adequately defined catchments.... An alternative is lysimetry, the use of appropriately sized tanks that can be precisely monitored and adequately replicated.' Davie *et al.* (2006) also discuss some problems associated with lysimeters, including the single large weighing type used by Campbell (1987), Campbell and Murray (1990), and Fahey *et al.* (1996). Interestingly, this concern was not for the lack of replication but for assessment of fog deposition. Similar criticism was also applied by Davie *et al.* (2006) to the non-weighing lysimeters used, in replicate, at nine sites on the upland snow tussock grasslands of eastern and Central Otago.

Two additional issues which Davie *et al.* (2006) raise with the non-weighing lysimeters are over-exposure producing an 'edge effect' and ecological representation, particularly with inter-tussock cover. They then follow this comment with another: 'Care was taken in the Holdsworth and Mark study to ensure the single tussock lysimeters were surrounded by similar vegetation.' They also repeat a concern of McSaveney and Whitehouse (1988) that a single plant may cause a 'fog-drip shadow surrounding it' .... a 'situation less critical with larger lysimeters', even though this issue had been addressed and dismissed with a detailed assessment in the earliest publication on the use of non-weighing lysimeters in Otago by Rowley (1970). We believe that the series of about 90 non-weighing lysimeters, with a range of replicated, representative cover types, in the snow tussock grasslands on the Otago uplands has shown statistically significant differences in water yields between cover types, with different simulated management regimes, and with location. Some of these results have been confirmed by catchment studies. Exceptionally high water yields from certain particularly fog-prone sites such as the southern Lammerlaw Range are further reflected in the podsolised nature of the yellow brown earth soils, as determined by pedologist Dr J. Churchman at the highest yielding site (Site 4) and reported by Holdsworth and Mark (1990; p. 21).

There are undoubtedly problems associated with the use of catchments and lysimeters, both the weighing and non-weighing types, in differentiating between rain and fog as to the source of the water inputs in water budget studies. Direct measurements of fog deposition on the dominant snow tussock foliage, using the relevant actual or simulated vegetation cover, as has been attempted several times on the Otago uplands (Mark *et al.*, 1980; Mark, 1998), are more robust. The use of stable isotope analyses of relevant components of the water balance, as by Ingraham and Mark (2000), we believe, have provided a more critical and thorough approach to assessing this issue.

Conclusions

We concur with the findings of several other researchers that the upland tall snow tussock grasslands of Otago provide a valuable ecosystem service in producing very high yields of water, relative to any alternative type of ground cover (Mark and Dickinson, 2008). However, we reject the recent claim by Davie *et al.* (2006) that the stable isotope study of Ingraham and Mark (2000) was defective in confirming earlier claims from lysimeter studies that deposition of water on tussock leaves from not-infrequent fog makes a significant contribution to these high yields.

We find the criticism of Davie *et al.* (2006) of the interpretation of the stable isotopic data by Ingraham and Mark (2000) to be burdened by prior commitment. While Davie *et al.* (2006) may not accept the simple, straightforward hydrologic interpretations presented by Ingraham and Mark (2000) we fail to see why arguments were proposed that contained a complete disregard of the understanding of the systematics of stable isotopic fractionation.

Concern expressed by Davie *et al.* (2006) that prolonged residence of water in the soil profile could have resulted in that sampled by Ingraham and Mark (2000) as lysimeter/groundwater having originated from rain-water collected from an earlier period, by perhaps 'several months', seems irrelevant to the results obtained from the isotopic analysis by Ingraham and Mark (2000). The generally freely available soil moisture in the solum of the upland snow tussock grasslands at the relevant study sites, including within the lysimeters, together with the lysimeter designs, plus information from other studies cited by Davie *et al.* (2006), make it unlikely that the age of the lysimeter/ground water sampled was more than six months old and thus not a factor in the results obtained by Ingraham and Mark (2000). This conclusion is in the context of the isotope study by Bonell *et al.* (1990) which showed water discharged in some streams at Glendhu to be a mixture of 'old' water sourced from a shallow, unconfined groundwater reservoir, and 'new' water from saturated overland flow.

The relatively high water yields from upland tall tussock grassland systems and the contribution of low evapo-transpiration by the dominant snow tussock grasses are not in dispute, as Davie *et al.* (2006) state. Neither are the relatively low interception losses from this vegetation type (Pearce *et al.*, 1984; Campbell and Murray, 1990), nor the low canopy water-storage capacity of the grassland, of *c.* 0.5 mm (Campbell and Murray, 1990) being questioned. It is important in this context, however, to distinguish between the **upland tall snow tussock grasslands** and tussock grasslands generally, which Davie *et al.* (2006) often fail to do. We maintain that gains of water by fog deposition on the dominant tall snow tussock cover, which still persists over much of the Otago uplands, and elsewhere in New Zealand, is both real and an important ecosystem service, as Mark and Dickinson (2006; 2008) have emphasised.

Ecological trade-offs involving snow tussock grasslands and other upland land-use options, including pasture grassland development and afforestation, must be carefully addressed in any planning exercise (Mark and Dickinson, 2008). Provision of clean fresh water is an essential ecosystem service. The maintenance and/or restoration of upland tall tussock grassland vegetation cover in good condition in order to maximise water yield is a highly significant issue to be addressed in important water supply catchments. This is regardless of whether the water is being extracted in-stream or as groundwater. Given the increasing demands for fresh, clean water for a range of human uses, including retention of minimum flows adequate for conservation and recreation needs, the valuable ecosystem service of water production provided by upland indigenous snow tussock grasslands, in good condition, should be formally recognised in land-use planning responsibilities of local authorities. Such formal recognition is generally lacking at present, even within Otago, which contains the country's most water-short region and where most of the relevant research has been conducted. Such recognition would be an important component of central government's current Sustainable Water Programme of Action and should also be incorporated into a National Policy Statement and National Environmental Standard, now being considered under the Resource Management Act.

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