

# Maximizing water yield with indigenous non-forest vegetation: a New Zealand perspective

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Provision of clean freshwater is an essential ecosystem service that is under increasing pressure worldwide from a variety of conflicting demands. Water yields differ in relation to land-cover type. Successful resource management therefore requires accurate information on yields from alternative vegetation types to adequately address concerns regarding water production. Of particular importance are upper watersheds/catchments, regardless of where water is extracted. Research in New Zealand has shown that, when in good condition, indigenous tall tussock grasslands can maximize water yield relative to other vegetation cover types. A long-term hydrological paired-catchment study revealed reductions (up to 41% after 22 years) in water yielded annually from an afforested catchment relative to adjacent indigenous grassland. Furthermore, a stable isotope assessment showed that water from fog may substantially contribute to yield in upland tussock grasslands. The tall tussock life-form and its leaf anatomy and physiology, which minimize transpiration loss, appear to be the differentiating factors. Thus, maintaining dominance of such cover is important for water production, especially in upland catchments. Ecological analogues and integrated land-use planning are discussed in the context of this essential ecosystem service. Water management programs in other countries are reviewed and that of South Africa is commended as a model.

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There is an increasing call for economic models and land-management frameworks to incorporate the value of ecosystem services into their accounting, planning, and decision making (Prato 1999). These services, such as the provision of clean water, are becoming increasingly vulnerable worldwide, as demand increases and environments degrade (Körner *et al.* 2006; Metzger *et al.* 2006). This vulnerability is made more acute by competing and often conflicting demands, and the complexity of associated ecologi-

cal, social, and political issues (Bohensky and Lynam 2005). Water is essential to human life and welfare, and demand is increasing. Many people worldwide are already living in conditions of serious water scarcity, and with increasing concentration of populations in urban areas, future supply and availability is a globally sensitive issue (Bolund and Hunhammar 1999; Vörösmarty *et al.* 2000; Jenerette and Larsen 2006). Estimates indicate that nearly half of humanity depends directly or indirectly on water yield from mountain catchments (Körner *et al.* 2006).

Ecosystems, the services they provide, and the people who use and manage them, form complex adaptive systems (Bohensky and Lynam 2005). Resolution of system-wide problems involves a combination of behavioral, institutional, and technical factors, and an integrated approach, very likely including trade-offs, is needed to achieve desired benefits (Bohensky and Lynam 2005; Jackson *et al.* 2005). Those factors related to the supply of freshwater include draw-off for domestic use versus storage for hydro-electricity or irrigation, often with associated displacement of people and downstream effects on biological conservation and other ecosystem services. Tree plantations for carbon sequestration, which cause reduction in water yield, may present a similar situation. Such matters offer considerable challenges to societies. Global climate change introduces additional complexity, with many scenarios projecting major shifts in precipitation and temperature regimes (Beniston 2003; Giorgi 2006; IPCC 2007). Development of frameworks for integrating ecosystem services with socioeconomic benefits are therefore essential for sustainable

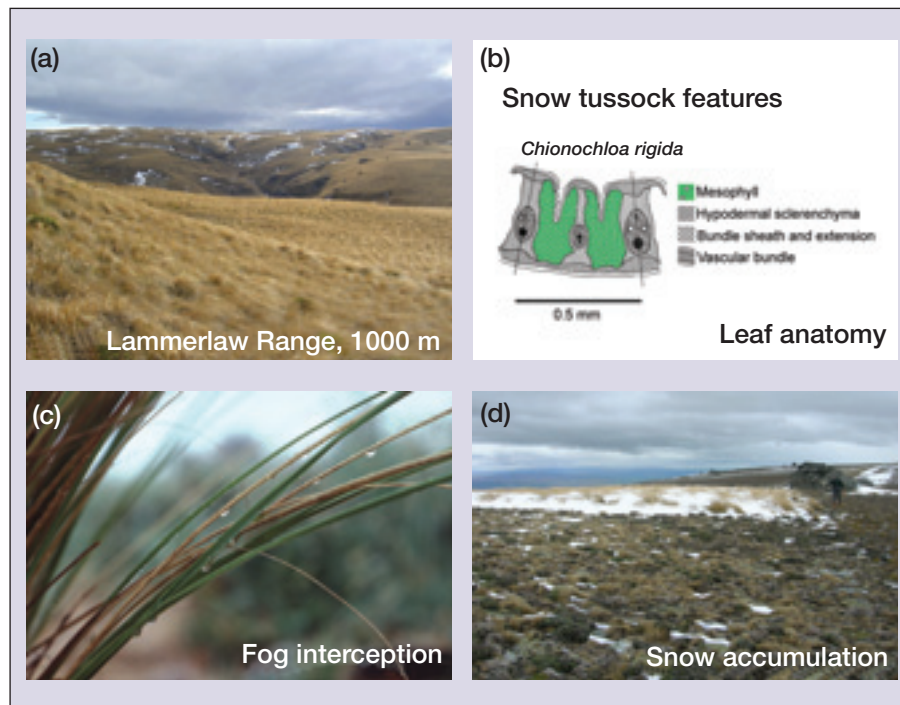
## In a nutshell:

- Provision of clean freshwater is an essential ecosystem service which is becoming less available globally due to increasing demand
- Different land-cover types can substantially affect water yields; these effects can be important in upland catchments/watersheds, where the potential for water production is usually greatest
- Trade-offs between wood production/carbon sequestration and water production should be carefully evaluated through integrated land-use planning, particularly in important water-supply areas
- Many countries, including New Zealand, are addressing water-supply, allocation, and quality problems with varying degrees of success; we commend the comprehensive South African National Water Act of 1998 as a model

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**Figure 1.** (a) Special features of narrow-leaved snow tussock (*Chionochloa rigida*) grassland (pictured here in Dunedin City's water supply catchment) make it particularly efficient for water yield, yielding its leaf anatomy. (b) A camera lucida outline of a cross section of part of a mature leaf. The stomata (not shown) are adjacent to the photosynthetic mesophyll tissue and confined to the innermost reaches of the furrows on the concave side of the leaf. These furrows tend to close when the leaf rolls in response to low humidity, thus further reducing water loss. Adapted from Mark (1975) and reproduced with permission. (c) The diffuse, fine, elongated leaves of tussock allow them to intercept water droplets from fog, up to  $0.5 \text{ L hr}^{-1}$  by a single tussock in dense fog without measurable rain. (d) An area of snow tussock planted in 1974, on the crest of the Old Man Range in south-central New Zealand, showing their ability to accumulate snow on this highly exposed site.

landscape planning and maintenance of natural capital (de Groot 2006), as well as for societal well-being (MA 2005).

## ■ Issues

### **Land use, vegetation cover, and water production**

The links between land use and water production, and the contribution of a particular vegetation cover to runoff and groundwater supplies, have been studied most convincingly through the use of paired catchments, with one of the pair undergoing treatment (eg planted or cleared) and the other remaining as a control or reference (Brown *et al.* 2005). New Zealand has a history of paired catchment studies, which are now being integrated into global syntheses of the effects of vegetation change on water yield (Brown *et al.* 2005; Farley *et al.* 2005; Adams and Fowler 2006). These syntheses have confirmed that different land covers usually deliver different water yields, seasonally and annually, as well as in times of high and low flows. Achieving an understanding of catchment hydrodynamics and the inter-relationship with vegetation type is therefore essential to developing an inte-

grated approach to land-use planning aimed at maximizing water yield at the catchment level. Influences of changing land use and vegetation cover on water yield are particularly important in the upper source areas, where environmental changes may result in reduced downstream flows and groundwater availability.

### **Tall tussock (bunch) grassland ecosystems**

Ecosystems dominated by tall tussock (bunch) grasses occur in various parts of the world, particularly in oceanic temperate conditions such as may be found in New Zealand (Figure 1a), the tropical high mountains, and sub-Antarctic regions, but are much less common in temperate continental areas (Mark *et al.* 2000). In New Zealand, upland indigenous tall tussock grasses are resistant to wind and snow cover. In comparison to most other dominant plants here, these grasses also have relatively low water loss (transpiration), because their stomata are located in deeply incised furrows on the concave side of the rolled leaves (Mark 1975; Figure 1b). Moreover, the

degree of rolling increases in response to desiccation (Clearwater 1999). These attributes, combined with the plant's morphology, render them efficient traps for precipitation in the form of rain (Pearce *et al.* 1984), snow, or fog (Ingraham and Mark 2000; Figure 1 c, d). These grasses are thus important for regional hydrology (Holdsworth and Mark 1990; Fahey and Jackson 1997).

Ecologically, there are some useful analogies that can be made with the New Zealand situation. In Ecuador, for example, research has shown that the *páramo* tall bunch grass ecosystems (Hofstede *et al.* 2003) are ecologically equivalent to those in New Zealand (Mark *et al.* 2000). As with the upland tall tussock grassland catchments in New Zealand (Webb *et al.* 1999), the *páramo* of the tropical high Andes plays an important role in maintaining soil moisture (Farley *et al.* 2004). Elsewhere in the tropics, such as on Mount Kenya in East Africa, where water supply is also critical, studies of the effects of fire on Afro-alpine vegetation, which includes tussock grassland ("moorland") have focused on plant diversity rather than ecosystem function (eg Wesche 2006). To date, the adjoining forests have received more attention in relation to resource-management conflicts (Kiteme and Gikonyo 2002).

### Ecological trade-offs between afforestation and tall tussock grasslands

Since the creation of the Clean Development Mechanism (CDM) under the Kyoto Protocol, understanding the role of tree plantations in carbon sequestration has become increasingly important (Farley *et al.* 2004). The CDM enables developed countries to offset their emissions with afforestation or reforestation in developing countries. Such planting has occurred in Ecuador, and while carbon sequestration has not been the primary motivation for exotic tree plantations in New Zealand, carbon offset procedures have now been introduced. In the Ecuadorian páramo, bioclimatic conditions lead to slow rates of decomposition and high carbon storage. Here, following afforestation with *Pinus radiata*, soil-water retention declined with stand age, with an associated loss in soil carbon (Farley *et al.* 2004). Losses were linked to changes in soil organic matter and moisture retention (Hofstede *et al.* 2002), in addition to water losses attributed to greater canopy interception and evapotranspiration of trees when compared with grasslands (Fahey and Jackson 1997; Engel *et al.* 2005).

Such decreases in soil carbon may not be solely a result of afforestation; previous land use, site preparation, species planted, climate, and soil type all influence water retention (Farley *et al.* [2004] and references therein). However, there are important issues to be addressed in balancing afforestation/reforestation with maintenance of a vegetation cover that maximizes water yield. Some strategies to address global climate change and the increase in greenhouse gases may be fundamentally at odds with water yield considerations (Jackson *et al.* 2005), with the loss of vegetation types that maximize water yield and provide substantial carbon storage having important consequences.

### Water yield issues in New Zealand's upland indigenous tussock grasslands

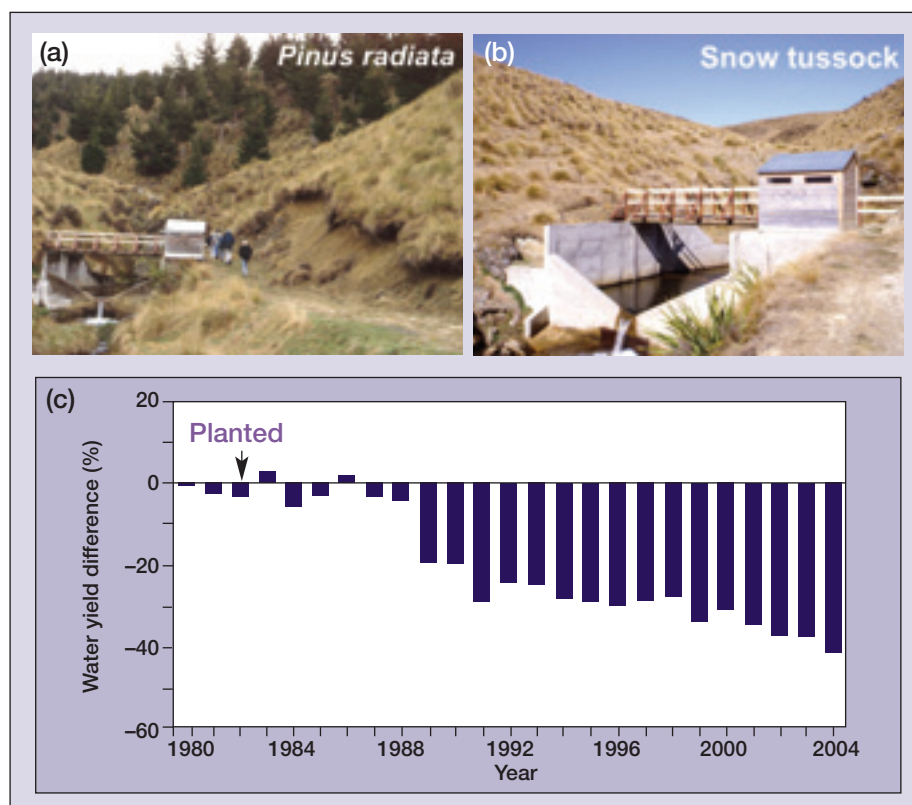
New Zealand is relatively well endowed with natural water. Precipitation is generally evenly distributed seasonally, with annual falls varying regionally from 330 to > 10 000 mm (Mark 1993). Most urban areas depend on clean, freshwater either directly from catchments or indirectly from groundwater. Furthermore, much of this water comes from upland catchments, where precipitation is generally higher and evapotranspiration is less than at lower altitudes (Figure 2). Thus, land uses in these uplands may have considerable bearing on water yield, as well as on low and high flows. Though the term “ecosys-



**Figure 2.** View up the eastern slope of the Old Man Range (1650 m), south-central New Zealand, from 750 m on the lower slopes, showing mixed fescue-snow tussock montane grassland (foreground), which gives way to pure snow tussock sub-alpine grassland above ~900 m. Snow-lie areas in the high-alpine zone on the upper slopes above ~1300 m have remnant slim snow tussock, blue tussock, herbfield, and cushionfield. Values for mean annual precipitation (Pptn) and mean annual air temperature (MAT) are shown (right) for five sites (610 m, 910 m, 1220 m, 1380 m, and 1590 m) up this altitudinal sequence, with those for the town of Alexandra (150 m) on the valley floor (bottom values) indicating the importance of the upper slopes for water yield.

tem services” is relatively new to the natural resource vocabulary, their value is not. Rivers were singled out as important resources throughout human occupation in New Zealand, first by Māori in pre-European times, and soon after European settlement in the 1840s, when river boards were established. This mainly reflected concerns about land stability and erosion. Although the importance of guaranteed water supply and quality was appreciated, the record of integrated management is patchy, with many substantial challenges still to be faced (Memon 1997; Memon and Selsky 2004).

Temperate native grasslands are considered to be the world’s “most beleaguered biome” (Henwood 1998). In the New Zealand uplands, their cover, composition, and structure have been variously transformed by pastoral farming (burning and grazing, mostly by introduced sheep) during the European phase of settlement, with some associated adverse impacts on soil, water, and biodiversity values. Although reasonably substantial areas remain (Mark and McLennan 2005), there is cause for concern. Degradation or loss of these ecosystems is not easily remedied. Successions within the tall tussock grasslands are prolonged because of the slow growth rates and long life spans of individual tussocks (Mark 1993). These features led to the observation that the tussock grassland “has many of the characteristics of a forest and few of those of a short rotation pasture, it is the product of a long, slow development and, like a forest, it is much



**Figure 3.** V-notch weirs recording water yield from each of the adjacent Glendhu paired catchments at 460–670 m, Lammerlaw Range, south-central New Zealand. (a) *Pinus radiata* was planted in 1982 over 67% of the 310-ha catchment at 1250 stems  $\text{ha}^{-1}$  (b) while the adjoining lightly grazed ( $\sim 1$  sheep per ha) reference 218-ha catchment remains dominated by narrow-leaved snow tussock (*Chionochloa rigida*) grassland. (c) The annual water yield difference (pine–snow tussock) between the two catchments up to 2004 is shown at the base. Data provided by B Fahey.

easier to destroy than to rebuild” (Moore 1954). Tall tussock grasses increase in basal area through vegetative tillering, and their sparse mortality emphasizes their longevity. Once lost, re-establishment is very slow, even where a seed source is available (Mark 1993).

Research focusing on transformation of tall tussock grassland to exotic afforestation has revealed important effects. A paired-catchment study (Glendhu), in south-central South Island (Fahey and Jackson 1997) has shown a continuing and increasing reduction in annual water yield from a 310-ha catchment planted in *Pinus radiata* relative to an adjacent 218-ha reference catchment of lightly grazed tussock grassland (up to 41% after 22 years; Figure 3). Such results confirm the potential trade-offs involved with afforestation for carbon sequestration or other purposes.

Other research highlights the importance of the indigenous tall tussock grassland (at most, lightly grazed) in maximizing water yield in comparison with a range of other vegetation types. Lysimeter (device used to measure the water balance of an area of vegetation) studies of water yield in relation to upland plant cover in south-central South Island begun in 1966 were later extended to six other sites in the same and nearby regions (Figure 4).

Results from snow tussock grassland in non-weighing lysimeters indicated that a mean annual rainfall of 1348 mm returned 63% of this as water yield, surplus to evaporative losses (Mark and Rowley 1976). These figures were consistent with subsequent results from similar upland grassland in the nearby Glendhu catchment (see Figure 3), where a yield of 64% was recorded from a mean annual precipitation of 1305 mm (Pearce *et al.* 1984). The lysimeter-based water yields from upland tussock grassland were consistently greater than from the four other cover types studied. The yield from this grassland reached as much as 80% of the measured 1372 mm annual precipitation (and 86% for the snow-free 6 months) at one of the seven study sites (from 490 to 1340 m altitude); this was more than from a short turf of blue tussock (*Poa colensoi*) or even bare soil (Figure 4). Further, short, exotic pasture grassland at the lowest site (490 m; not shown in Figure 4), yielded < 1% of measured precipitation (Holdsworth and Mark 1990).

In another paired upland catchment study nearby, 75% of the treated snow tussock grassland catchment was burned in 1988 (Figure 4). When compared with the unburned reference catchment, a significant reduction in summer flows was measured in the early post-fire years (Duncan and Thomas 2004), with a 32% reduction in summer runoff in the second year and 19% in the third year. As tussocks recovered from the fire, relative water yield from the burned catchment gradually increased. A similar pattern was found with an earlier lysimeter study, and was explained by low transpiration of mature tussocks compared with young regrowth foliage, plus reduced interception of fog by the shorter canopy (Mark and Rowley 1976).

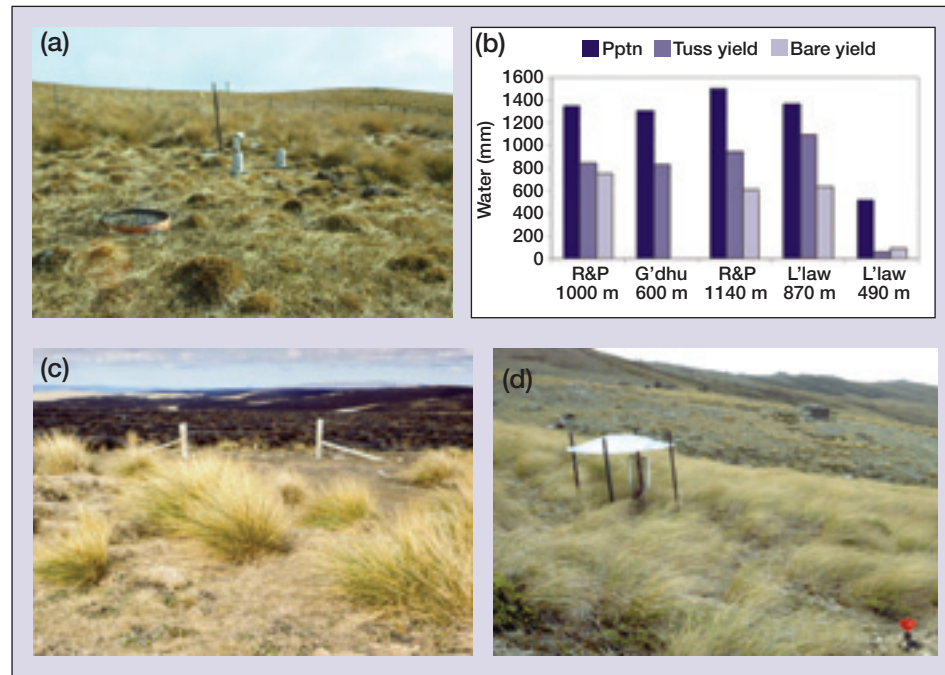
The entrapment (interception gain) of fog and its importance for water yield is well documented and accepted outside New Zealand (eg Bruijnzeel 2001; Olivier and Rautenbach 2002; Beiederwieden *et al.* 2005) but its role has been a source of controversy here (Holdsworth and Mark 1990). A stable isotope study (Ingraham and Mark 2000) provided further evidence that fog may contribute substantially to water yield in the upland tussock grasslands of south-central South Island. In this study, the isotopic composition of rain, fog, and groundwater was established for three upland sites (Figure 4) over two consecutive snow-free seasons. Fog, as an early-stage condensate from

saturated air relatively close to the ground, had been shown to have a higher proportion of the heavy stable isotopes (of oxygen and hydrogen) than rain, which is a later-stage condensate (Ingraham 1998). In the upland study, fog was consistently more enriched in the heavy isotopes than rain, and the isotopic composition of the groundwater indicated a mixture of fog and rain in subequal proportions (Ingraham and Mark 2000; Figure 5). Such results reinforce the importance of intact tall tussock grasslands in delivering water, particularly from fog-prone upland ecosystems.

#### Securing essential water supplies in New Zealand

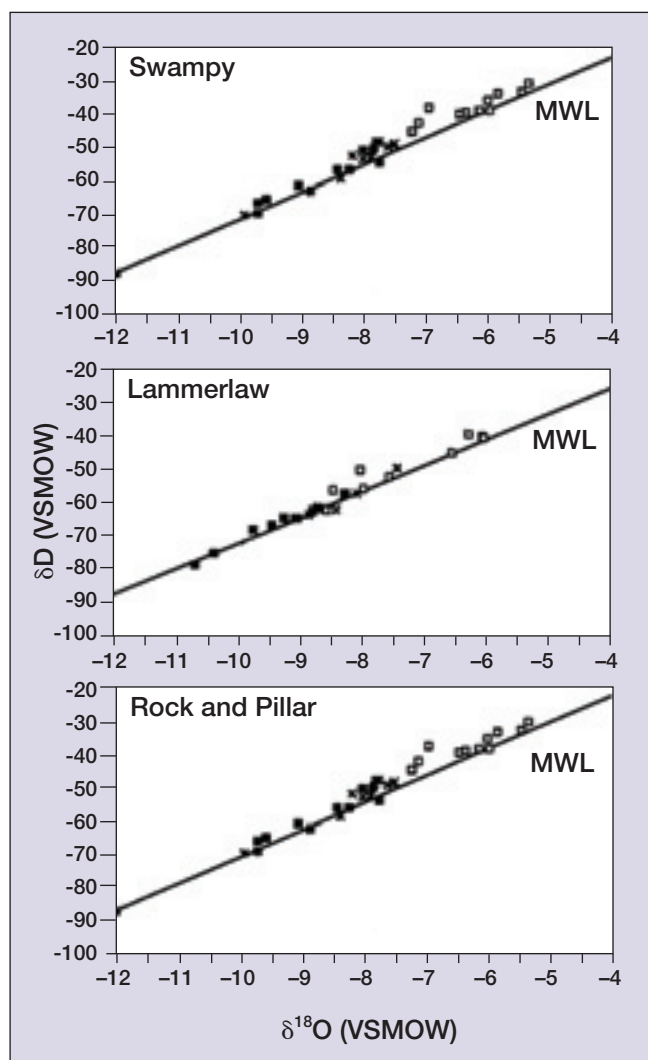
Recognizing the importance of a secure water supply in relation to land-use decisions is not without precedent (Bohensky and Lynam 2005), including in New Zealand. For example, the Dunedin City Council acknowledged the importance of tall tussock grassland cover by purchasing an upland property in its water supply catchment in the 1980s (Dunedin City Council 2006). Furthermore, the Council's involvement in the review of the lease on an adjacent, government-owned 12 000-ha property in 2001 was aimed at obtaining long-term security of water supply by ensuring retention of tall tussock grassland in good condition. Indeed, the economic value of the water resource from this area was confirmed with the recent establishment of the Te Papanui Conservation Park (approximately 22 000 ha), which is dominated by tall tussock grassland (see Mark *et al.* 2003). The economic study (Butcher Partners Ltd 2006) assessed the value of water produced from the Park to be about NZ\$136 million (US\$92.8 million), in relation to providing an alternative supply.

Under New Zealand's Resource Management Act of 1991, regional councils must seek to protect and enhance the environment, and safeguarding water supply and quality is an important component of these responsibilities (Memon 1997). Councils can develop regional water plans to establish objectives and criteria for water management (Snelder and Hughey 2005). The Otago Regional Council, whose area of jurisdiction covers one of New Zealand's driest regions, has an operational Water



**Figure 4.** (a) Lysimeter in snow tussock grassland on the Lammerlaw Range, measuring water yield associated with bare soil. Sheltering tussock has been cut. Other lysimeters are located in the undisturbed tussock grassland beyond. (b) Annual water yields associated with snow tussock grassland and bare soil in relation to precipitation at five sites on the Otago uplands: lysimeters at 1000 m on the Rock and Pillar Range; the weir measurements from the Glendhu catchment at ~600 m (G'dhu; Pearce *et al.* 1984); lysimeters at 1140 m on the Rock and Pillar Range (R&P), 870 m and 490 m on the Lammerlaw Range (L'law; Holdsworth and Mark 1990). (c) Deep Creek catchment, 1120 m, soon after burning in 1988, where summer flows in the post-burn period were significantly reduced in relation to that in the nearby unburned catchment (Duncan and Thomas 2004). (d) The devices installed to catch water derived from either fog (fine nylon mesh screen, oriented normal to the prevailing fog-bearing wind and mounted under a large metal umbrella) or rain (red funnel in right foreground). Water was collected in bottles beneath paraffin, for later analyses of heavy isotopes (Ingraham and Mark 2000).

Plan which includes an overview of catchment hydrology through a monitoring network. However, this plan does not address water production from important supply catchments, nor is there a land plan which could have addressed vegetation cover in relation to its effect on water production. Dunedin City obtains more than 60% of its water supply from upland sources, where indigenous tall tussock cover still remains. However, land-management history and contemporary pressures for land-use intensification, combined with exotic afforestation and hydro-electric development, are leading to increasing conversion from this indigenous cover, despite rising demands for water. Such developments have consequences, particularly in relation to water yield and carbon storage (Farley *et al.* 2005; Jackson *et al.* 2005), and an explicit recognition and economic evaluation of such trade-offs seems essential. The situation may be further aggravated by global warming and the predicted redistribution of precipitation. Such evaluations appear not to have featured in the policy-making processes to date. However, a potentially important precedent was established by local government in New Zealand in 1998,



**Figure 5.** Stable isotope (oxygen and hydrogen) composition of the fog ( $\square$ ), rain ( $\blacksquare$ ), and groundwater ( $\times$ ) samples collected at each of three sites on the Otago uplands, south-central New Zealand: Swampy Summit (736 m asl), Lammerlaw Range (870 m asl), and Rock and Pillar Range (1140 m asl), are shown with the meteoric water line (MWL). The isotope values are presented in delta ( $\delta$ ) notation, which expresses the difference between the measured ratios of a sample and a world standard reference, over the measured ratio of the reference, as follows:  $\delta_{\text{sample}} = (1000 \text{ ratio}_{\text{sample}} - \text{ratio}_{\text{reference}}) / \text{ratio}_{\text{reference}}$ .  $\delta$  values are expressed as parts per thousand. Negative  $\delta$  values indicate that the sample has less of the heavier isotope than the reference Vienna Standard Mean Ocean Water (VSMOW). Reproduced courtesy of Ingraham and Mark (2000).

under the Resource Management Act. The Tasman District Council refused to grant a resource consent for exotic afforestation of a water supply catchment on the basis that this would reduce the quantity of water downstream for an established horticultural use. The decision was subsequently appealed in, but upheld by, the Environment Court. We are not aware of subsequent legal challenges, despite comparable situations in other parts of the country.

## Discussion and conclusions

### A New Zealand perspective

An integrated approach to land-use planning, evaluating ecosystem services, recognizing trade-offs, and incorporating the need to protect water supply and quality is needed (Prato 1999; de Groot 2006) in New Zealand (Memon 1997) and elsewhere (Farley *et al.* 2005). Land-cover type clearly affects the quantity of water yield, as has been shown for upland snow tussock grassland regions in New Zealand. It is critical that governments – locally, regionally, and nationally – integrate these considerations into their planning responsibilities. Ecosystem services require careful evaluation in conjunction with the development of economic incentives. In this context, management of upland water supply catchments to maximize water production is crucial. Reliance on the Resource Management Act (RMA) requirement to protect outstanding natural landscapes and/or key indigenous vegetation through district (local government) plans is too ad hoc to safeguard water yield in supply catchments. Similarly, the outcomes of the current tenure review of the South Island pastoral leasehold lands cannot be relied upon to secure protection of important upland water supply catchments.

There is a need to ensure that land-use planning in New Zealand recognizes the role of different vegetation cover types in catchment/watershed areas important for water supply. There are some encouraging initiatives. The Government recently launched a Water Awareness Campaign and the New Zealand Landcare Trust, with funding from the Ministry for the Environment, is administering an Integrated Catchment Management Project. This aims to integrate the management of land, water, and other biological resources in order to achieve sustainable and balanced use. The Government's current Sustainable Water Programme of Action is a major initiative, but at this stage it addresses neither the general issue of water yield nor the specific effects of land cover on water production in upland catchments (Ministry for the Environment 2006).

Retention or restoration of tall tussock grassland cover, where it exists in water supply catchments, could be a specific requirement under the RMA. Given the increasing demands on the country's freshwater resources, this requirement could be linked explicitly to securing maximum water yield. Guidelines could incorporate the effects of land use on water production and water quality from upland supply catchments. Such guidelines should be added to the current Sustainable Water Programme of Action, which is intended as the basis of a new National Policy Statement and National Environmental Standard under the RMA (Ministry for the Environment 2006).

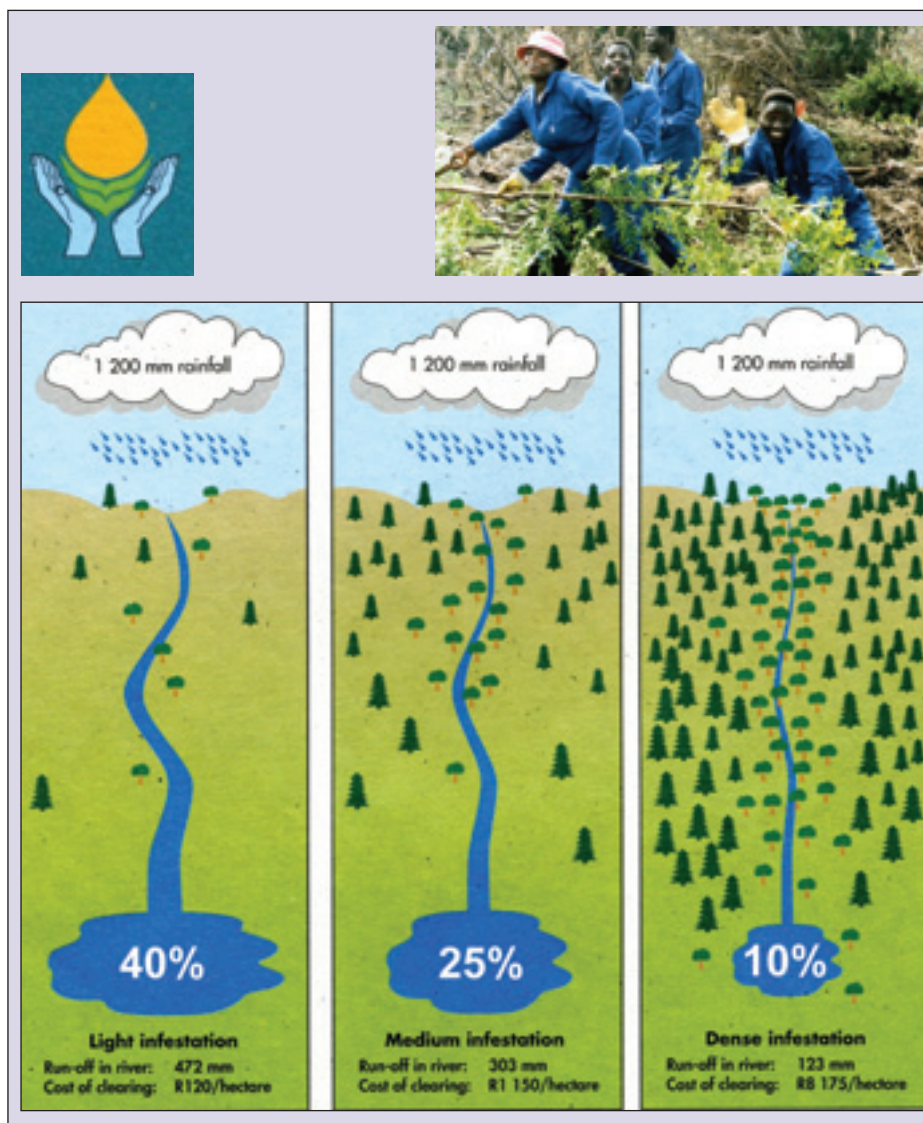
### International perspectives

Many other countries have also introduced programs aimed at understanding and managing freshwater

resources. One of the earliest and best known initiatives, and one which serves as a model, is South Africa's Working for Water program. Launched in 1995, this initiative integrates environmental, economic, and social-cultural aspects. Invading alien woody species, mostly of *Pinus*, *Eucalyptus*, and *Acacia*, are removed using local and otherwise unemployed, disadvantaged groups. Restoration of the rich indigenous biodiversity of the shrubby *fynbos* and other natural ecosystems is achieved while substantially increasing water yield (van Wilgen 2004; Figure 6). The program now operates within the context of the National Water Act of 1998, arguably the most comprehensive water legislation in the world. The Act mandates the Department of Water Affairs and Forestry to manage land so as to ensure there is a "reserve" (a baseline water flow for domestic and ecological uses) at all times. There is also great interest in levying major extractors of water.

Considerable overseas funding supports the program, which, in 2002, had an annual budget exceeding 400 million rand (US\$54.1 million). This investment is considered cost-effective in relation to the alternative of dam construction for increased water retention. The program has recently been reviewed through a special symposium (Macdonald 2004), which identified several research challenges. Almost 1.2 million ha of invasive alien vegetation had been cleared by the end of 2003, or about 12% of the infested areas, which is a major achievement. However, existing knowledge needs assessment, so that clearing operations can be more effectively prioritized in relation to water-related benefits (Görgens and van Wilgen 2004). Elsewhere in Africa, there are other initiatives. For instance, prevention and resolution of water supply and use conflicts in the Mount Kenya Highland-Lowland System are being addressed by catchment-based stakeholder groups and Water Users' Associations, with the support of the Ministry of Water Development (Kiteme and Gikonyo 2002).

Australia, the world's driest continent, has experienced



**Figure 6.** Promotional material for the South African Working for Water program. This poster emphasizes the degree to which invading alien woody species reduce water yield (from a 1200 mm annual rainfall) as the invasive trees gain increasing dominance in the system (percentages indicate water yields). The photo at top shows local people employed in the clearing of invasive species from the land. Adapted and reproduced with permission from Department of Water Affairs and Forestry (1996).

serious water problems, in particular agrochemical pollution and increasing salinization from clearance and irrigation. The country has recently suffered its most severe drought on record. Tension has been increased by recent wildfires and by the predicted, prolonged El Niño weather pattern. Prime Minister John Howard recently announced an AU\$300 million (US\$232.6 million) aid package for the rural sector, stating that more would be available if necessary. Major water reform in Australia was initiated in 2004, with the establishment of a National Water Commission under Federal Government legislation ([www.nwcgov.au/water\\_fund](http://www.nwcgov.au/water_fund)). The Commission is an independent statutory authority of seven commissioners, appointed for their expertise in water-related fields, and reports directly to the Prime Minister. Its main

functions are to administer two programs under an Australian Government Water Fund – the AU\$1.6 billion (US\$1.2 billion) Water Smart Australia and the AU\$200 million (US\$155.1 million) Raising National Water Standards programs. The latter is directed at implementing the National Water Initiative (water accounting, emerging water markets, water planning and management), improving integrated water management across Australia (irrigation and other rural water, water-dependent ecosystems, integrated urban water management) and improving knowledge and understanding of Australia's water resources. Australia also has a Community Water Grants program that funds communities to encourage the wise use of water. Another major development is an AU\$10 billion (US\$7.8 billion), 10-point plan, announced by Prime Minister Howard in January 2007. This initiative aims to improve water-use efficiency and to address the serious over-allocation and overuse of water in rural Australia. Emphasis is on the country's largest river basin, the Murray-Darling, which occupies about 15% of Australia's land mass. This "National Plan for Water Security" includes improvements in governance, technology, irrigation, the distribution network, security, and imposition of a sustainable cap on water use, while improving the health of rivers and wetlands. The Plan will also accelerate implementation of the National Water Initiative (Prime Ministerial Press Statement 2007).

In the US, there has been a long history of sub-alpine forest manipulation to enhance water production, particularly in the central and western mountains (Kittredge 1948), but issues remain. Controversy surrounds water yield from the semi-arid bunch grass and sagebrush rangeland communities, and the role of encroaching woody vegetation (Wilcox 2002). Much of the information is anecdotal or speculative, but recent results from monitoring stream flow in a series of small (first order) experimental and reference watersheds in the Texas Hill Country indicated "little or no effect...except where springs are present" (Wilcox *et al.* 2005). Since then, Wilcox *et al.* (2006) have reported that, for upland sites with deep drainage, conversion from woody to herbaceous vegetation may result in annual water savings of 40–80 mm. Such swings have been observed only in small catchments to date, and confirmation at larger scales awaits further research. However, some integrated catchment planning initiatives have been suggested. For example, along the US–Mexico border, a watershed approach has been advocated for intergovernmental coordination and management of sensitive areas to help ensure maintenance of natural functions, including water supply (Steiner *et al.* 2000).

China is currently implementing a sustainable water resource strategy (Yang and Pang 2006), considered vital to addressing water-related issues that have hampered recent economic development. With a per-capita availability of freshwater only about one quarter of the world

average, China faces a serious imbalance between supply and demand. Several factors exacerbate the problem: poor water-resource development, wasteful usage, and pollution. China's central government initiated several studies and reports in the early 1990s, considering sustainable water-resource development, relationships among water supplies, the economy, and society, water financing, and water conservation. Based on these studies, "Water Agenda 21" was formulated in 1998, to develop a sustainable water-resource strategy for the country. Yang and Pang (2006) discuss the implementation of this strategy, particularly the approaches used to address water problems, to meet the basic needs of urban inhabitants, agriculture, and the environment. Emphasis is on improved water allocation, more efficient use, and stronger protection of water resources. Protection plans have been developed that include monitoring and alarm systems for water quantity and quality, the protection of wetlands and other water sources, and integrated resource management. Action plans have been formulated for several major watersheds: the Yangtze, Yellow, Huai, Hai and Luan, Songhua and Liao, and the Pearl. Yang and Pang (2006) also describe progress toward improving urban living standards, balancing economic development and poverty alleviation, securing food supplies, conserving water and soil, and protecting ecosystems. The national plan encourages the general public to become more aware of the need for water conservation and recommends that traditional methods for conserving water be replaced with new technologies and institutional arrangements to facilitate a holistic approach to water management (Yang and Pang 2006).

At a transboundary level, the Water Governance Reform of the Mekong Region is based on a 1995 agreement between Thailand, Laos, Cambodia, Myanmar, and the Yunnan province of China. Here, a range of political, economic, environmental, social, and administrative systems have been introduced at different levels of society. These are to regulate development and management of water resources and provide water services, along with protected area management, in headwater regions (Hirsch 2006). Considerable foreign financial aid characterizes this attempt at holistic management of a finite water resource.

A major recent development has been the release of the Millennium Ecosystem Assessment (MA 2005). This promotes interaction among economists, social scientists, and ecologists, allowing tests of frameworks in practical situations (eg Nkomo and van der Zaag 2004; Bohensky and Lynam 2005). Overall, however, the MA found that the challenge of reversing the degradation of ecosystems while meeting increasing demands for their services will involve far-reaching changes in policies, institutions, and practices that are not currently underway. The MA indicated that many options exist to conserve or enhance ecosystem services in ways that can reduce negative trade-offs or provide positive relationships with other

ecosystem services. For water, the options presented are: payments for ecosystem services provided by watersheds, improved allocation of freshwater resources to align incentives with conservation needs, increased transparency of information regarding water management and representation of marginalized stakeholders, development of water markets, increased emphasis on the use of the natural environment and measures other than dams and levees for flood control, and investment in science and technology to increase the efficiency of water use in agriculture.

In the context of the MA, considerable challenges remain for water resource planning in New Zealand, especially in relation to the application of responsibilities under the Resource Management Act 1991 (Memon and Selsky 2004; Snelder and Hughey 2005), and in the integration of ecosystem services into economic models and decision making. Beyond New Zealand, national and international agreements dealing with ecosystem services and human well-being, and emphasizing the critical importance of freshwater, could be implemented, as recommended in the Millennium Ecosystem Assessment (MA 2005). From our perspective, the South African National Water Act of 1998 provides a positive integrated model for future action. As the world's "water towers", mountains are of critical importance and there is a great need to improve current management and monitoring of upland water (Viviroli *et al.* 2003), particularly in relation to land cover and condition.

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