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TABLE 4. MOISTURE CONTENT (% DRY WEIGHT) OF VEGETATION AND SOIL SAMPLES COLLECTED IMMEDIATELY BEFORE THE EXPERIMENTAL BURNS. FIGURES ARE THE MEAN (± SEM) OF FIVE SAMPLES PER PLOT AND THREE PLOTS PER TREATMENT.

	DEEP STREAM		MT BENGER	
	SPRING	SUMMER	SPRING	SUMMER
Surface litter	9.2 ± 0.7	8.5 ± 0.4	8.1 ± 0.8	16.4 ± 1.8
Tussock base litter	111.5 ± 16.0	100.5 ± 11.6	201.4 ± 19.0	240.3 ± 3.0
Live tussock tillers	115.8 ± 1.2	119.5 ± 0.3	107.5 ± 1.6	109.5 ± 1.6
Soil (0–5 cm)	57.9 ± 5.0	54.2 ± 1.1	99.1 ± 6.5	114.2 ± 14.8
Soil (5–10 cm)	52.7 ± 1.7	50.1 ± 1.5	66.4 ± 1.6	77.4 ± 5.8

TABLE 5. NUTRIENT RETURN (kg/ha) FROM ASH DEPOSITED BY THE EXPERIMENTAL BURNS. FIGURES ARE THE MEAN (± SEM) OF FIVE SAMPLES PER PLOT AND THREE PLOTS PER TREATMENT.

	DEEP STREAM		MT BENGER	
	SPRING	SUMMER	SPRING	SUMMER
Nitrogen	0.06 ± 0.01	0.09 ± 0.01	0.03 ± 0.01	0.04 ± 0.01
Phosphorus	0.14 ± 0.02	0.12 ± 0.01	0.07 ± 0.03	0.09 ± 0.02
Potassium	0.81 ± 0.10	0.65 ± 0.05	0.34 ± 0.15	0.41 ± 0.08
Calcium	0.75 ± 0.14	0.57 ± 0.03	0.19 ± 0.10	0.22 ± 0.04
Magnesium	0.19 ± 0.03	0.13 ± 0.01	0.10 ± 0.05	0.11 ± 0.02
Sulphur	0.02 ± 0.00	0.04 ± 0.00	0.01 ± 0.00	0.01 ± 0.00

Figure 10. Tall-tussock grassland at Deep Stream, 6 weeks after a summer burn. Note the rapid recovery of the spaniard (*Aciphylla aurea*), and the high proportion of exposed soil.

Relationships between biomass loss and measurements of plant and soil moisture were complicated by the fact that the summer burns at Mt Benger occurred during a tussock mast flowering season, which substantially increased the above-ground tussock biomass relative to that present at the time of the spring burns (Table 2). When these data were removed, there was a highly significant relationship between biomass loss and soil moisture$_{(0\text{–}5\ \mathrm{cm})}$ (slope = –0.856, SE_{slope} = 0.144, t = 5.95, df = 7, $P < 0.001$), and a significant relationship between biomass loss and the moisture content of the tussock bases (slope = –0.351, SE_{slope} = 0.071, t = 4.94, df = 7, P = 0.002) (Fig. 11). Using Spearman rank correlation coefficients, the Fire Weather Index System's FFMC component was the best predictor of biomass loss (r_s = 0.75, n = 9, P = 0.023) followed equally by DMC, ISI, BUI and FWI (r_s = 0.70, n = 9, P = 0.042), and DC (r_s = 0.00, n = 9, P = 0.893).

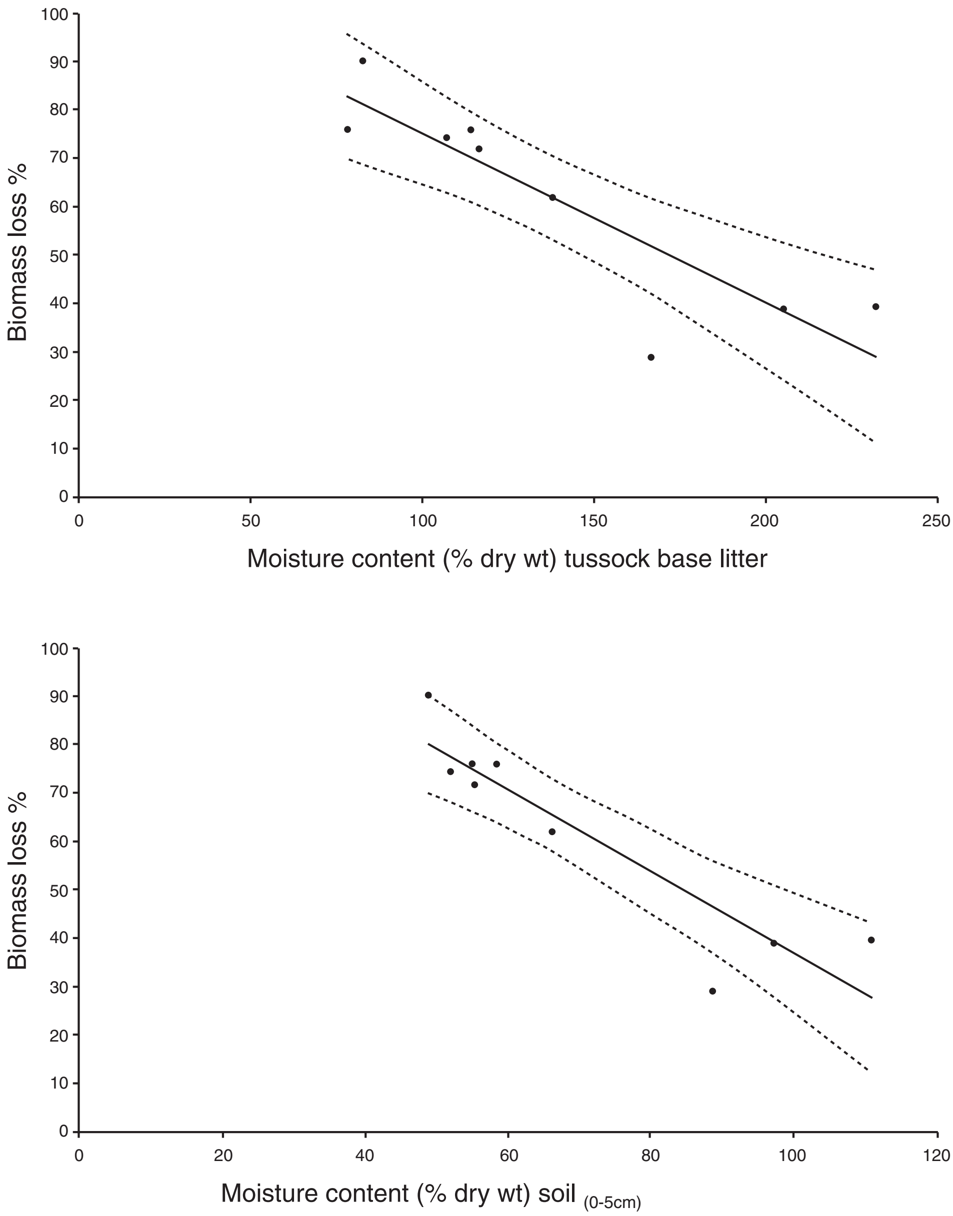

Figure 11. Relationship between above-ground biomass loss and measurements of plant and soil moisture.

4.4 TILLER AND TUSSOCK MORTALITY

Spring burns killed an average of 35% of tussock tillers at Mt Benger (Table 6), but did not cause the death of individual tussocks (Table 7). This is in contrast to the situation at Deep Stream, where spring burns were responsible for the death of nearly 80% of tussock tillers and 21–70% of tussocks. Summer burns killed an average of 83% of tillers at Deep Stream and 87.4% at Mt Benger. They also killed 50.7% of tussocks on the Deep Stream plots, but were not directly responsible for the death of tussocks at Mt Benger. In summer-burned plots, tiller and tussock mortality was exacerbated by the failure of many resprouted tillers to survive the sub-zero winter temperatures. This meant that overall tiller mortality on summer-burn plots rose to 91.6% at Mt Benger and 92.7% at Deep Stream, when the post-burn tiller counts were repeated the following spring. This, in turn, increased tussock mortality from 50.7% to 65.3% at Deep Stream, and from 0% to 27.0% at Mt Benger.

4.5 TUSSOCK FLOWERING AND SEEDLING ESTABLISHMENT

At both sites, unburned tussocks flowered heavily (masted) in 1998–99 and 2005–06, and produced a smaller number of inflorescences in 1999–00 and 2002–03 (Fig. 12). As expected, spring-burned tussocks at both sites flowered during the season after fire. At Deep Stream, this coincided with a natural flowering event, but at Mt Benger it was clearly fire-related. Spring-burned tussocks at Mt Benger also flowered during the second and fifth seasons after fire (2002–03 and 2005–06), both of which were natural flowering seasons.

TABLE 6. TILLER MORTALITY (%) IN *Chionochloa rigida* TUSSOCKS AFTER SPRING AND SUMMER FIRES AT DEEP STREAM AND MT BENGER. FIGURES ARE THE MEAN (± SEM) OF TEN TUSSOCKS PER PLOT AND THREE PLOTS PER TREATMENT.

	SPRING FIRES	SUMMER FIRES	
	FIRE	FIRE	FIRE + WINTER FROSTS
Deep Stream	77.9 ± 5.9	83.0 ± 2.7	92.7 ± 2.7
Mt Benger	35.1 ± 3.1	87.4 ± 2.5	91.6 ± 2.1

TABLE 7. TUSSOCK MORTALITY (%) AFTER SPRING AND SUMMER FIRES AT DEEP STREAM AND MT BENGER. FIGURES ARE THE MEAN (± SEM) OF 50 TUSSOCKS PER PLOT AND THREE PLOTS PER TREATMENT.

	SPRING FIRES		SUMMER FIRES	
	AREA OF GOOD SURVIVAL	AREA OF POOR SURVIVAL	FIRE	FIRE + WINTER FROSTS
Deep Stream	21.3 ± 2.4	70.0 ± 5.3	50.7 ± 1.3	65.3 ± 5.5
Mt Benger	0	0	0	27.0 ± 4.6

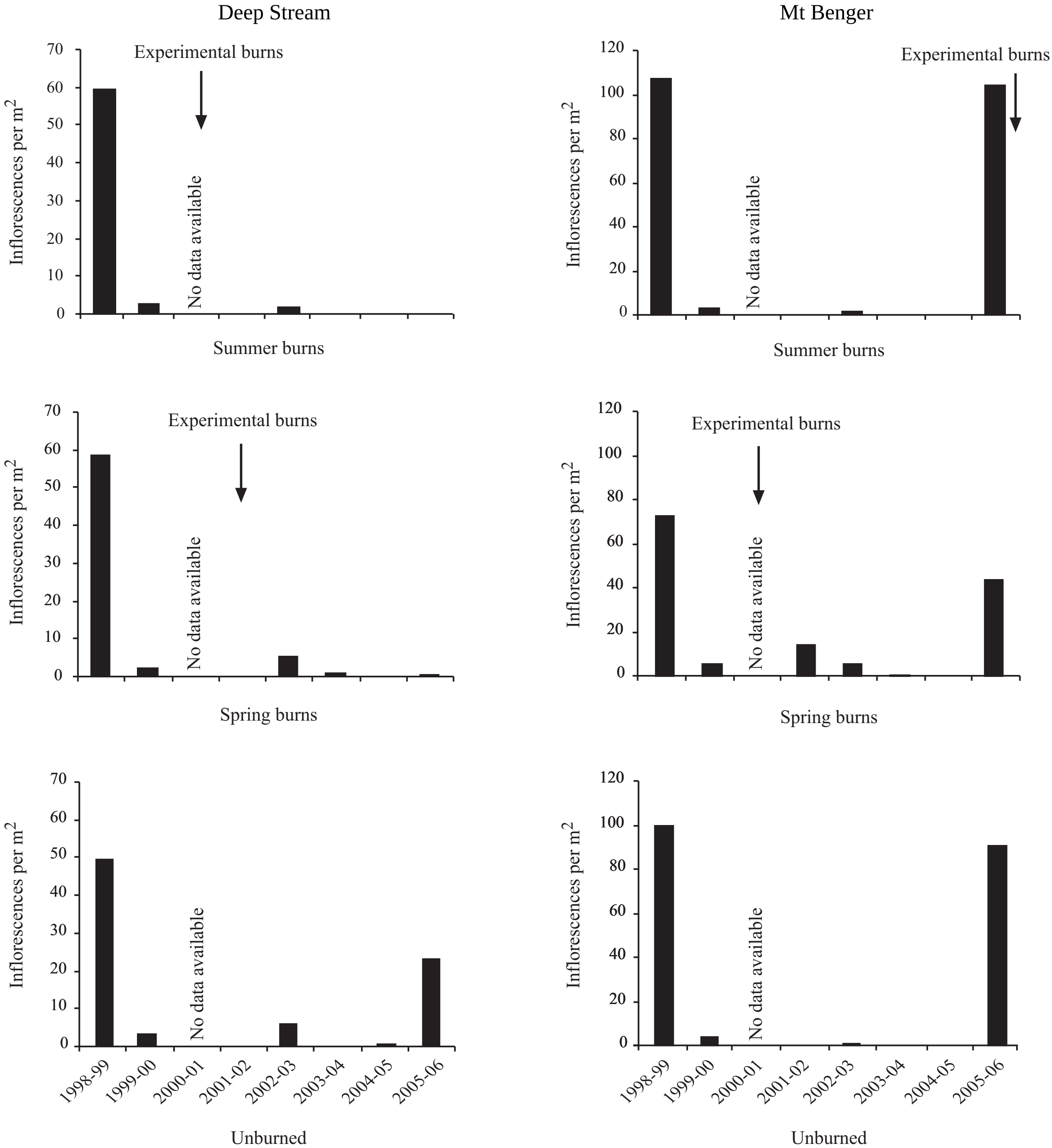

Figure 12. Effect of spring and summer fires on the flowering intensity of *Chionochloa rigida* tussocks at Deep Stream (left column) and Mt Benger (right column). Values are the mean of ten samples per plot and three plots per treatment.

Their flowering intensity 5 years after fire was approximately half that of the unburned plants. At Deep Stream, little or no flowering was observed during the 2005–06 mast year on spring- or summer-burned plots; this was largely due to the dramatic decline in tiller density as a result of the fires. The consequences of fire for autumn-burned tussocks at Mt Benger, where the experimental fires were delayed until March 2006, are yet to be determined.

Over the period of the study, unburned plots at Deep Stream and Mt Benger averaged 5.5 ± 0.6 and 3.9 ± 0.5 tussock seedlings/m², respectively (Fig 13).

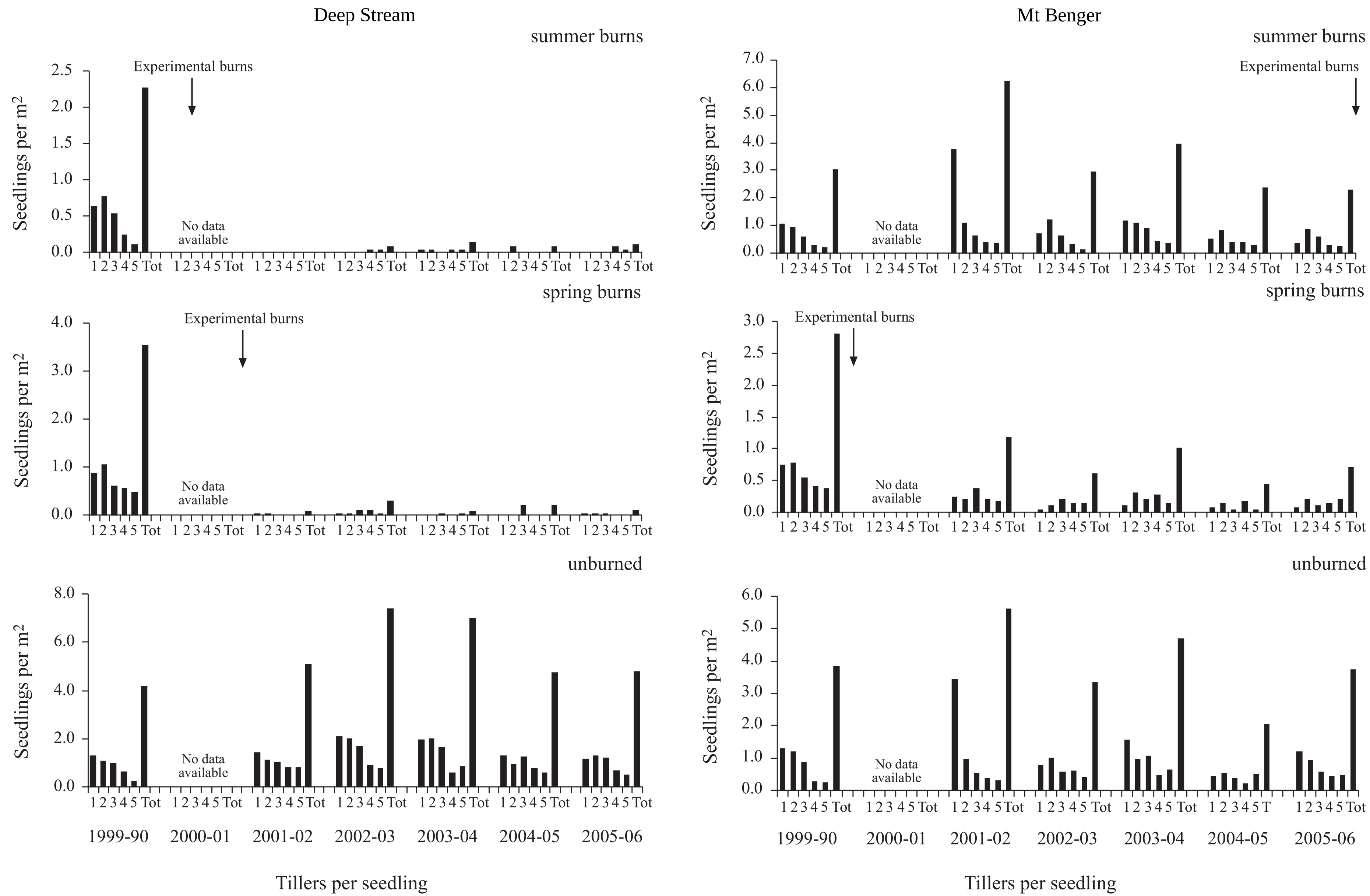

Figure 13. Effect of spring and summer fires on the seedling density of *Chionochloa rigida* tussocks at Deep Stream (left column) and Mt Benger (right column). Labels on the *x*-axis denote the density of individual (1–5) tiller cohorts and total (Tot) seedling density. Values are the mean of ten samples per plot and three plots per treatment.

At Mt Benger, spring burning markedly reduced seedling densities, despite the damp conditions, and 5 years later, there was little sign of a return to pre-burn levels. At Deep Stream, the drier spring and summer burns had an even harsher impact, reducing densities of tussock seedlings by 97.3% and 98.7%, respectively, over the same period.

4.6 CHANGES TO THE STRUCTURE AND COMPOSITION OF THE GRASSLANDS

At Mt Benger, the combination of spring burning under damp conditions and excluding stock from the post-fire grasslands did not substantially alter the structure and composition of the vegetation. Six months after the spring burns, all of the plots showed vigorous regrowth of both tussock and inter-tussock vegetation, and 5 years later there was an intact tall-tussock grassland (Fig. 14), albeit of lower stature than that of the adjacent unburned stands. In contrast, the summer-burned plots at Mt Benger are still in the early stages of post-fire recovery (Fig. 14). High levels of tiller mortality make it unlikely that these grasslands will return to complete tussock cover in the near future, even in the absence of grazing by stock. As with the spring burns at this site, the summer fires had little effect on the ground-cover layer

At Deep Stream, where both the spring and summer burns killed a considerable percentage of the existing tussocks and removed much of the ground-cover layer (Fig. 10), the outlook is very different. Within 12 months of the burns, browntop (*Agrostis capillaris*), which is present throughout the tussock grasslands at Deep Stream, had formed an almost unbroken sward over all of the burned areas; although existing plants of the spaniard *Aciphylla aurea* resprouted vigorously after the burns, these failed to survive. Five years later, browntop remains the

Figure 14. Tussock grassland at Mt Benger, 1 year after a summer burn (foreground) and 5 years after a spring burn (mid-ground). This site has not been grazed since the burns.

dominant cover on all of the burned plots, the surviving tussocks are beginning to re-exert their presence (Fig. 15), and spaniard seedlings are once again common throughout the grasslands.

Figure 15. Spring- (foreground) and summer- (background) burned plots at Deep Stream 5 years after fire, with scattered *Chionochloa rigida* tussocks amidst the browntop (*Agrostis capillaris*).

5. Discussion and conclusions

Studies of fire impacts in New Zealand indigenous grasslands have generally been initiated in response to past fire events (e.g. Wilson 1976; Espie 2002) and have used a space-for-time approach to interpret post-fire responses (e.g. Gitay et al. 1992; Gitay & Wilson 1995). Where experimental treatments have been imposed, these have generally not been at a scale that allowed fire behaviour to be determined, or that replicated the conditions encountered during pastoral burns or wildfire events (e.g. O'Connor & Powell 1963; Payton et al. 1986). This failure to characterise the severity of fire events and to adequately simulate 'real-world' situations has hampered our ability to interpret the short-term response of the grasslands to fire and to predict longer term trends (e.g. Allen & Partridge 1988; Gitay et al. 1991; Calder et al. 1992). The present study, which we believe is the first to incorporate fire behaviour into an ecological study of a New Zealand tall-tussock grassland, sought to rectify these problems by including the measurement of fire parameters in the experimental design and by using larger-scale (1-ha) plots that more closely approximate pastoral burns or wildfire events (Payton & Pearce 2001).

5.1 EXPERIMENTAL DESIGN

Our study was designed to test the consequences of early- and late-season fires for the long-term sustainability of tall-tussock grassland communities. The experimental design set up a two-way comparison: early- v. late-season fires and damp v. dry burns. At the outset, the expectation was that the damp burns would occur in spring and the dry burns later in the season. As it turned out, however, conditions for both the early- and late-season burns at the more drought-prone Deep Stream site were relatively dry, while at Mt Benger both the early- and late-season burns took place under damper conditions. Thus, despite failing to achieve damp early-season burns at Deep Stream and dry late-season burns at Mt Benger, we were still able to preserve the original two-way comparison, albeit not in the manner originally envisaged.

This raises the question of whether the two sites, which represent opposite ends (higher altitude, damper climate v. lower altitude, drier climate) of the tall-tussock grassland continuum, can be considered as replicates for the purposes of examining fire impacts. The only conclusive way of answering this question would be to repeat the experiment and reverse the treatments (i.e. early- and late-season fires under dry conditions at Mt Benger, and vice versa); however, given the financial and administrative challenges that this would pose, such an experiment is unlikely to happen. What we can say is that, where it is possible to make direct comparisons between the sites, the results are not inconsistent. Examples include the relationship between plant and soil moisture and biomass loss, the post-fire flowering response in the tall-tussocks, and the depression of tussock seedling density.

The other point that needs to be remembered when considering the applicability of our results to 'real-world' situations is that, for reasons of safety, none of the burns were carried out during periods of high fire risk, which regularly occur throughout the eastern South Island high country during late summer and autumn. The data, therefore, do not represent the full range of conditions over which fires in tall-tussock grasslands might be expected to occur.

5.2 BIOMASS, CARBON AND NUTRIENT LOSSES

Detailed breakdowns of the biomass and nutrient composition of natural plant communities are rare, probably because of the time-consuming, and therefore costly, nature of producing them. They are, however, necessary if we are to understand the type and magnitude of the losses sustained as a result of fire, and the shifts in resource allocation in the post-fire vegetation.

In the present study, biomass increased on all plots between the initial assessment in 1997–98 and the assessment carried out within 12 months of the experimental burns, which suggests that both sites were still recovering from past fire events and/or a lengthy history of mammalian grazing. Biomass loss due to fire was least when the grasslands were burned under damp spring conditions, which is the practice used for pastoral management burns (O'Connor 1982), and greatest when soil and vegetation conditions were driest. All of the fires burned the bulk of the loosely compacted plant material. When conditions were damp, as was the case for both the early- and late-season fires at Mt Benger, the tussock bases and ground-cover vegetation (which together constitute a considerable proportion of the above-ground biomass) remained largely unburned. As the grasslands dried out, the fires burned a progressively greater proportion of this more tightly compacted material. Under the driest conditions we encountered (the late-season burns at Deep Stream), most of the ground-cover vegetation was burned and the tussock bases were reduced to stumps no more than 8–10-cm high. The late-season fires at Mt Benger consumed a higher percentage of biomass than was expected due to a spike in the quantity of loosely compacted plant material, which was brought about by a mast flowering season for the tussocks. The best predictors of biomass loss were the moisture content of the top 5 cm of soil and the moisture content of litter at the base of the tussock. For the fire weather indices, those that were more responsive to short-term climatic fluctuations, and which therefore more closely reflected the flammability of the grassland at the time of the burn, were better predictors of biomass loss than those that reflected longer-term trends. Thus, FFMC > DMC, ISI, BUI and FWI, which are > DC (see Appendix 1 for definitions).

Four previous studies have quantified total (above- and below-ground) plant biomass for tall-tussock grasslands, and three of these have included estimates of the nutrient pools (Williams 1977; Williams et al. 1977; Meurk 1978; Evans 1980; O'Connor et al. 1999). However, none presented a breakdown of the non-tussock component of the grassland, although Evans (1980) alluded to the fact that these data were obtained. Results from these studies showed considerable variability in the size of the biomass (39–87 t/ha) and nutrient pools, and no consistent differences between tussock species or between major biomass compartments (live v. dead; above- v. below-ground) (O'Connor et al. 1999). Biomass estimates for *Chionochloa rigida* grasslands, all of which had remained unburned for over a decade, ranged from 62 to 87 t/ha, which is higher than the values reported in the present study. The reason for this is not immediately obvious, but may result from differences in methodology (calculations based on tiller density and weight v. direct harvest). All grasslands showed a high percentage of dead organic matter in the above-ground biomass, a feature which acts to conserve nutrients in an unburned environment but greatly increases their vulnerability to loss by fire (Scott 1999).

There is a widely held view that the repeated use of fire and the limited application of fertiliser in managing indigenous tussock grasslands for livestock production have progressively depleted the biomass and nutrient capital of these ecosystems (Basher et al. 1990; McKendry & O'Connor 1990; Working Party on Sustainable Land Management 1994). It is therefore somewhat surprising to find that this study appears to be the first to have directly measured biomass, carbon and nutrient losses resulting from fire in tall-tussock grasslands.

In our study, carbon and nutrient losses were proportional to biomass losses, indicating that fire temperatures were sufficiently high to volatilise key elements such as nitrogen, phosphorus, potassium and sulphur, which are known to be limiting for plant growth in high-country environments (O'Connor & Harris 1992). We found no evidence of substantial nutrient input from ash deposited by the fires, which confirms earlier findings that nutrient return from tall-tussock grassland fires is minimal and would not be expected to provide a boost to plant growth in the post-fire environment (O'Connor & Powell 1963; Mark 1965a).

5.3 TILLER AND TUSSOCK MORTALITY

In the present study, spring burns under damp conditions killed around a third of tussock tillers, but did not cause the death of tussocks, and clearly had the least disruptive effect of any fire regime on the structure and composition of the grasslands. Where grasslands were burned under drier conditions or later in the growing season, tiller mortality increased dramatically and there was a greater risk of tussocks being killed. Two factors appear to be important in determining the vulnerability of tillers and therefore tussocks to fire: the timing of the burns and the dryness of the grasslands.

Burns in late winter or early spring, before the tussock tillers break their winter dormancy, allow the reallocation of nutrients (principally N and K) from the roots to the new leaf tissue (Payton et al. 1986). Once growth is underway, this option would appear to be reduced or precluded, which we suggest may reduce the chance of tiller survival. The likelihood that tillers will survive also depends on the ability of the tightly compacted plant material at the base of the tussock to shield the apical meristem from the short, sharp burst of heat generated by the fire. Damp tussock bases are little affected by fire, and we suggest they act as an effective heat shield for the majority of the tiller meristems. As the grasslands dry out and progressively greater proportions of the tussock bases are burned, the effectiveness of this heat shield can be expected to diminish, resulting in a greater proportion of the tillers failing to survive. The other damaging influence associated with the timing of the burns is frost. Tillers that resprouted after late-season fires were unable to sufficiently harden off their new foliage before the first autumn frosts, and failed to recover the following season. Thus, although the late-season fires at Mt Benger that occurred when the grasslands were damp did not kill tussocks, the frosts that followed did.

Conventional wisdom is that while fires kill tussock tillers, the combined effects of fire and grazing are required to kill tussocks (O'Connor & Powell 1963). There are, however, few data to support this contention. The only record we have been able to find of the fire-related death of tussock tillers is an illustration in Mark (1965b) showing increased tiller mortality in autumn-burned *Chionochloa rigida* tussocks on Coronet Peak compared with their spring-burned counterparts. Evidence for fire causing the death of tussocks is similarly scarce, and is at times contradictory. O'Connor & Powell (1963: 364) cited anecdotal evidence of 'the fatal effects of extremely severe fires such as occur in midsummer' from Barker (1953) and Raeside (1960), while in the same paper the authors reported their surprise that no tussocks died after a severe fire in early spring in which 'snow tussocks were burnt evenly down to butts of about 2 inches in height' (O'Connor & Powell 1963: 357). Fire during a period of severe drought is reported to have killed *C. rigida* tussocks in the Cardrona Valley, Central Otago (C.D. Meurk, pers. obs., in Basher et al. 1990). Our study showed that both early- and late-season fires can kill tussocks, and that conditions do not have to be extremely dry for this to happen. Our data do not allow us to reconcile the apparent difference between this result and that of O'Connor & Powell (1963).

5.4 SEEDLING ESTABLISHMENT

The recovery of tall-tussock grasslands after fire depends on the ability of the surviving tussocks to regain their former dominance, and of new individuals to establish themselves in the post-fire environment. The latter is especially important where fire has severely depleted tiller populations and killed tussocks. Our study showed reduced numbers of seedlings in the post-fire grasslands. As with other parameters, seedling densities were least affected when grasslands were burned under damp spring conditions, and dramatically reduced when conditions were drier. The other interesting feature of our data is the lack of a move back to pre-burn seedling densities 4–5 years after fire, which does not augur well for the recovery of the grasslands. The reason for the continued low densities of tussock seedlings in the post-burn grasslands is not clear. It may result from the destruction of existing seed banks during the burns, from reduced seed inputs (lack of a mast year) or from changes to the competitive environment after the fire. Which one or combination of these factors is responsible will become apparent only from analysis of a longer-term dataset.

Several studies have investigated regeneration patterns in unburned tall-tussock grasslands (Rose & Platt 1990, 1992; Lee et al. 1993), but only one has examined seedling recruitment and survival in a post-fire environment (Mark 1965b). In this study, Mark (1965a) recorded abundant *Chionochloa rigida* seedlings 8 months after a spring fire on the Old Man Range in Central Otago, and followed their fate under a grazed and an ungrazed treatment for a period of 3 years. The reason for this different response is unclear, but is likely to involve differences in microsites (Rose & Platt 1990) and the severity of the burns.

5.5 GENERAL APPLICABILITY OF RESULTS

In this study, we used intact swards of *Chionochloa rigida* grassland that had remained unburned for at least a decade, and had been retired from grazing, to compare and contrast the effects of early- and late-season fires under damp and dry conditions. Of the four treatments, only the early-season burns carried out under damp conditions appear to have had little lasting effect on the structure of the grasslands. Burning later in the season or when conditions were drier dramatically increased tiller mortality, killed tussocks and resulted in a loss of tall-tussock dominance in the post-fire grassland, at least over the short to medium term. The fact that the treatments produced such different outcomes serves to emphasise the need for careful assessment of the environmental conditions when planning tussock burns, and the importance of considering fire regimes when seeking to understand the trajectory of the post-fire grasslands.

The deterioration of tall-tussock grasslands throughout the South Island high country and their progressive replacement by short-tussock and mat-dominated plant communities is well documented (e.g. Connor 1964, 1965; Mark 1993), and there is ample evidence to implicate the combined influence of fire and grazing by farmed or feral animals (e.g. O'Connor 1982; Mark 1994) in this process. What has not been so clearly articulated is that fire alone can cause the demise of tall-tussocks and their replacement by species better able to establish in the post-fire environment.

6. Management recommendations

The authors make the following recommendations based on the key findings of this study:

- Fires in late winter or early spring, when soil conditions are damp, pose little threat to the long-term survival of tall-tussock grasslands. Because post-fire grasslands attract heavy grazing pressure, priority should be given to minimising the presence of farmed or feral animals for 1 or preferably 2 years after a burn, to ensure that the recovery of the post-fire grassland is not impeded.
- Fires later in the season, or when soil conditions are dry, have the potential to cause significant damage to tall-tussock grassland communities. Minimising their extent should be a priority wherever tussock cover is to be retained.
- The current experiment has the potential to yield a wealth of valuable information on the rates of change in unburned and ungrazed grasslands, as well as those that are recovering from fire. Key to this will be the maintenance of the perimeter fences and the exclosure plots. Provision should also be made for ongoing monitoring and dissemination of the results.
- The current experiment does not consider the consequences of continued grazing, with or without fire, on the long-term sustainability of tall-tussock grassland ecosystems. This would be the next logical step to take.

7. Acknowledgements

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8. References

Allen, R.B.; Partridge, T.R. 1988: Effects of spring and autumn fires on the composition of *Chionochloa rigida* tussock grassland, New Zealand. *Vegetatio 76*: 37–44.

Anderson, S. 2005: Forest and rural fire danger rating in New Zealand. Pp. 241–244 in: Colley, M. (Ed.): Forestry handbook. New Zealand Institute of Forestry, Christchurch.

Barker, A.P. 1953: An ecological study of tussock grassland, Hunters Hills, South Canterbury. *New Zealand Department of Scientific and Industrial Research Bulletin 107*: 1–58.

Barratt, B.I.P.; Ferguson, C.M.; Barton, D.M.; Johnstone, P.D. 2007: Impact of fire on tussock grassland invertebrate populations. Unpublished report prepared by AgResearch for the Department of Conservation. 104 p.

Basher, L.R.; Meurk, C.D.; Tate, K.R. 1990: The effects of burning on soil properties and vegetation: a review of the scientific evidence relating to the sustainability of ecosystems and land use in the eastern South Island hill and high country. *DSIR Land Resources Technical Record 18*. 93 p.

Blakemore, L.C.; Searle, P.L.; Daly, B.K. 1987: Methods for chemical analysis of soils. *New Zealand Soil Bureau Scientific Report 80*. 103 p.

Calder, J.A.; Wilson, J.B.; Mark, A.F.; Ward, G. 1992: Fire, succession and reserve management in a New Zealand snow tussock grassland. *Biological Conservation 62*: 35–45.

Connor, H.E. 1964: Tussock grassland communities in the Mackenzie Country, South Canterbury, New Zealand. *New Zealand Journal of Botany 2*: 325–351.

Connor, H.E. 1965: Tussock grassland communities in the middle Rakaia valley, Canterbury, New Zealand. *New Zealand Journal of Botany 3*: 261–276.

Espie, P. 2002: Vegetation and soil changes in semi-arid grassland after the Alexandra 1999 summer fire. Unpublished AgResearch contract report prepared for the Otago Regional Council. 38 p.

Evans, G.R. 1980: Phytomass, litter, and nutrients in montane and alpine grasslands, Craigieburn Range, New Zealand. Pp. 95–109 in Benecke, U.; Davis, M.R. (Eds): Mountain environments and subalpine tree growth. Proceedings of IUFRO workshop, November 1979, Christchurch, New Zealand. *New Zealand Forest Service Technical Paper No. 70*. 288 p.

Gill, A.M.; Knight, A.K. 1991: Fire measurement. Pp. 137–146 in Cheney, N.P.; Gill, A.M. (Eds): Conference on bushfire modelling and fire danger rating systems, 11–12 July 1988, Canberra, A.C.T. CSIRO Division of Forestry, Yarralumla, A.C.T.

Gitay, H.; Wilson, J.B. 1995: Post-fire changes in community structure of tall tussock grasslands: a test of alternative models of succession. *Journal of Ecology 83*: 775–782.

Gitay, H.; Wilson, J.B.; Lee, W.G.; Allen, R.B. 1991: *Chionochloa rigida* tussocks thirteen years after spring and autumn fire, Flagstaff, New Zealand. *New Zealand Journal of Botany 29*: 459–462.

Gitay, H.; Lee, W.G.; Allen, R.B.; Wilson, J.B. 1992: Recovery of *Chionochloa rigida* tussocks from fire in South Island, New Zealand. *Journal of Environmental Management 35*: 249–259.

Hennessy, K.; Fitzharris, B.; Bates, B.C.; Harvey, N.; Howden, S.M.; Hughes, L.; Salinger, J.; Warrick, R. 2007: Australia and New Zealand. Pp. 507–540 in Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J.; Hanson, C.E. (Eds): Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Hobbs, R.J.; Currall, J.E.P.; Gimingham, C.H. 1984: The use of 'thermocolor' pyrometers in the study of heath fire behaviour. *Journal of Ecology 72*: 241–250.

Leathwick, J.; Morgan, F.; Wilson, G.; Rutledge, D.; McLeod, M.; Johnston, K. 2002: Land environments of New Zealand. A technical guide. Ministry for the Environment, Wellington. 237 p.

Lee, W.G.; Fenner, M.; Duncan, R.P. 1993: Pattern of natural regeneration of narrow-leaved snow tussock *Chionochloa rigida* ssp. *rigida* in central Otago, New Zealand. *New Zealand Journal of Botany 31*: 117–125.

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

Mark, A.F. 1965b: Flowering, seeding, and seedling establishment of narrow-leaved snow tussock, *Chionochloa rigida*. *New Zealand Journal of Botany 3*: 180–193.

Mark, A.F. 1993: Indigenous grasslands of New Zealand. Pp. 361–410 in Coupland, R.T. (Ed.): Ecosystems of the world. Vol. 8B. Natural grasslands—Eastern Hemisphere. Elsevier, Amsterdam.

Mark, A.F. 1994: Effects of burning and grazing on sustainable utilisation of upland snow tussock (*Chionochloa* spp.) rangelands for pastoralism in South Island, New Zealand. *Australian Journal of Botany 42*: 149–161.

Mark, A.F., Dickinson, K.J.M. 2003: Temporal responses over 30 years to removal of grazing from a mid-altitude snow tussock grassland reserve, Lammerlaw Ecological Region, New Zealand. *New Zealand Journal of Botany 41*: 655–668.

McGlone, M.S. 2001: The origin of the indigenous grasslands of southeastern South Island in relation to pre-human woody ecosystems. *New Zealand Journal of Ecology 25*: 1–15.

McIntosh, P. 1997: Nutrient changes in tussock grasslands, South Island, New Zealand. *Ambio 26*: 147–151.

McKendry, P.J.; O'Connor, K.F. 1990: The ecology of tussock grasslands for production and protection. Centre for Resource Management, Lincoln University and University of Canterbury. 161 p.

Meurk, C.D. 1978: Alpine phytomass and primary productivity in central Otago, New Zealand. *New Zealand Journal of Ecology 1*: 27–50.

Molloy, B.P.J.; Burrows, C.J.; Cox, J.E.; Johnston, J.A.; Wardle, P. 1963: Distribution of subfossil forest remains, eastern South Island, New Zealand. *New Zealand Journal of Botany 1*: 68–77.

New Zealand Soil Bureau 1968: General survey of the soils of South Island, New Zealand. *Soil Bureau Bulletin 27*. 404 p.

O'Connor, K.F. 1982: The implication of past exploitation and current developments to the conservation of South Island tussock grasslands. *New Zealand Journal of Ecology 5*: 7–107.

O'Connor, K.F. 1986: The influence of science on the use of tussock grasslands. *Tussock Grasslands and Mountain Lands Review 43*: 15–78.

O'Connor, K.F. 1987: The sustainability of pastoralism. Pp. 161–188 in: Proceedings of the 1987 Hill and High Country Seminar, Lincoln College, Canterbury.

O'Connor, K.F.; Harris, P.S. 1992: Biophysical and cultural factors affecting the sustainability of high country pastoral land uses. Pp. 304–313 in Henriques, P.R. (Ed.): Sustainable land management: the Proceedings of the International Conference on Sustainable Land Management, November 1991. Hawke's Bay Regional Council, Napier.

O'Connor, K.F.; Powell, A.J. 1963: Studies on the management of snow-tussock grassland. I. The effects of burning, cutting and fertiliser on narrow-leaved snow tussock (*Chionochloa rigida* (Raoul) Zotov) at a mid-altitude site in Canterbury, New Zealand. *New Zealand Journal of Agricultural Research 7*: 354–367.

O'Connor, K.F.; Nordmeyer, A.H.; Svavarsdóttir, K. 1999: Changes in biomass and soil nutrient pools of tall tussock grasslands in New Zealand. Pp. 125–145 in Arnalds, O.; Archer, S. (Eds): Case studies of rangeland desertification. Proceedings from an international workshop in Iceland. *Rala Report No. 200*. Agricultural Research Institute, Reykjavik.

Parliamentary Commissioner for the Environment 1995: A review of the government system for managing the South Island tussock grasslands: with particular reference to tussock burning. Office of the Parliamentary Commissioner for the Environment, Wellington. 105 p.

Payton, I.J.; Lee, W.G.; Dolby, R.; Mark, A.F. 1986: Nutrient concentrations in narrow-leaved snow tussock (*Chionochloa rigida*) after spring burning. *New Zealand Journal of Botany 24*: 529–537.

Payton, I.J.; Pearce, G. 2001: Does fire deplete the physical and biological resources of tall-tussock (*Chionochloa*) grasslands? The latest attempt at some answers. Pp. 243–249 in Pearce, G.; Lester, L. (Eds): Bushfire 2001: proceedings of the Australasian Bushfire Conference, 3–6 July 2001, Christchurch, New Zealand.

Quikchem Methods Manual 1995: Lachat Instruments Division, Zellweger Analytics Inc., Milwaukee, Wisconsin, USA.

Raeside, J.D. 1960: An unsolved problem in soil and water conservation. *Proceedings of the New Zealand Society of Soil Science 4*: 18–23.

Rose, A.B.; Platt, K.H. 1990: Age-states, population structure, and seedling regeneration of *Chionochloa pallens* in Canterbury alpine grasslands, New Zealand. *Journal of Vegetation Science 1*: 89–96.

Rose, A.B.; Platt, K.H. 1992: Snow tussock (*Chionochloa*) population responses to removal of sheep and European hares, Canterbury, New Zealand. *New Zealand Journal of Botany 30*: 373–382.

Scott, D. 1999: Sustainability of New Zealand high-country pastures under contrasting development inputs. 1. Site, and shoot nutrients. *New Zealand Journal of Agricultural Research 42*: 365–383.

Stevens, G.; McGlone, M.S.; McCulloch, B. 1988. Prehistoric New Zealand. Heinemann, Auckland. 128 p.

Tolhurst, K.G. 1995: Fire from a flora, fauna and soil perspective: sensible heat measurement. Pp. 45–58 in McCaw, W.L.; Burrows, N.D.; Friend, G.R.; Gill, A.M. (Eds): Landscape Fires '93. Proceedings of an Australian Bushfire Conference, 27–29 September 1993, Perth, Western Australia. *CALMScience Supplement 4.* Department of Conservation and Land Management, Como, Western Australia.

Van Wagner, C.E. 1987: Development and structure of the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ontario. *Forestry Technical Report 35*. 37 p.

Williams, P.A. 1977: Growth, biomass, and net productivity of tall-tussock (*Chionochloa*) grasslands, Canterbury, New Zealand. *New Zealand Journal of Botany 15*: 399–442.

Williams, P.A.; Nes, P.; O'Connor, K.F. 1977: Macro-element pools and fluxes in tall-tussock (*Chionochloa*) grasslands, Canterbury, New Zealand. *New Zealand Journal of Botany 15*: 443–476.

Wilson, H.D. 1976: Vegetation of Mount Cook National Park, New Zealand. *National Parks Authority Scientific Series No.1*. Department of Lands and Survey, Wellington. 138 p.

Working Party on Sustainable Land Management 1994: South Island high country review. Final Report. South Island High Country Review Working Party. 184 p.

Appendix 1

NEW ZEALAND FIRE WEATHER INDEX SYSTEM

The Fire Weather Index (FWI) System is the core component of the New Zealand Fire Danger Rating System. It provides the basis for a uniform method of rating fire danger throughout New Zealand (Anderson 2005). It consists of three fuel moisture codes and three fire behaviour indices that are derived from daily observations of weather conditions taken at 1200 hours NZST.

Fuel moisture codes

The following codes are ordered according to length of the response (shorter to longer term).

Fine Fuel Moisture Code (FFMC) Uses temperature, relative humidity, wind speed and daily rainfall to provide a rating of the moisture content of litter and other cured fine fuels. It is an indicator of flammability and hence the relative ease of ignition of fine dead fuels.

Duff Moisture Code (DMC) Rates the moisture content of loosely compacted soil organic layers, based on temperature, relative humidity and daily rainfall. For tussock grasslands, it provides a measure of the dryness of ground-layer vegetation (mosses, forbs, etc.) and decaying plant material.

Drought Code (DC) Uses temperature and daily rainfall to provide a rating of the moisture content of deep, compacted organic soil layers. It is a good indicator of general soil dryness and, for tussock grasslands, and would be expected to be a useful indicator of the dryness of the base of tussock clumps and hence overall tussock fuel consumption.

Fire behaviour indices

Initial Spread Index (ISI) Provides a rating of the expected rate of fire spread, and is determined using Fine Fuel Moisture Code (FFMC) and wind speed data.

Buildup Index (BUI) Combines the Duff Moisture Code (DMC) and Drought Code (DC) to provide a rating of the total amount of fuel available for combustion, and would be expected to correlate with the amount of fuel that is actually consumed by the fires.

Fire Weather Index (FWI) Uses ISI and BUI to provide a rating of potential fire intensity, and would be expected to be a useful indicator of flame length. It also serves as a general index of fire danger.

Appendix 2

PRE-BURN ASSESSMENT OF BIOMASS, CARBON AND NUTRIENT POOLS (kg/ha) AT THE DEEP STREAM STUDY SITE (DECEMBER 1997–FEBRUARY 1998)

Values are the mean of five samples per plot and nine plots per site.

	BIOMASS	C	N	P	K	Ca	Mg	S
Grasses, rushes and sedges								
Adventive grasses[a]	1338.1	601.1	10.76	1.13	6.57	1.62	1.27	1.54
Chionochloa rigida	3771.0	1793.2	23.90	3.36	31.11	2.04	2.52	4.25
Poa colensoi	123.2	54.6	1.05	0.13	0.59	0.11	0.08	0.15
Rushes and sedges	12.4	5.4	0.12	0.01	0.06	0.01	0.01	0.01
Forbs								
Aciphylla aurea	272.7	127.6	1.54	0.27	5.21	1.96	0.38	0.23
Celmisia gracilenta	108.4	49.9	1.23	0.13	1.08	0.57	0.24	0.14
Hieracium spp.[b]	7.5	3.3	0.07	0.01	0.14	0.05	0.02	0.01
Oreobolus pectinatus	77.2	34.5	0.60	0.06	0.33	0.08	0.09	0.07
Raoulia subsericea	0.8	0.4	0.01	0.00	0.01	0.01	0.00	0.00
Minor forbs	136.6	60.4	1.64	0.18	1.83	0.96	0.43	0.20
Shrubs								
Coprosma cheesemanii	30.1	14.4	0.29	0.03	0.22	0.19	0.10	0.02
Acrothamnus colensoi	419.8	210.1	2.60	0.31	1.75	2.14	0.49	0.26
Leucopogon fraseri	36.6	18.2	0.31	0.03	0.08	0.30	0.06	0.03
Muehlenbeckia axillaris	31.4	16.3	0.20	0.02	0.08	0.19	0.04	0.03
Pentachondra pumila	871.7	450.9	5.67	0.47	2.28	5.19	1.21	0.61
Pernettya macrostigma	2194.2	1086.2	15.36	1.65	9.38	9.23	3.19	2.11
Minor shrubs	1.3	0.7	0.01	0.00	0.01	0.01	0.00	0.00
Lower plants								
Lycopodium spp.[c]	373.5	177.7	3.16	0.36	1.75	0.29	0.35	0.30
Coarse mosses[d]	43.1	19.4	0.30	0.03	0.20	0.08	0.07	0.03
Fine mosses	946.7	430.2	7.84	0.85	3.97	2.56	1.41	0.79
Lichen	104.4	44.9	0.55	0.06	0.30	0.09	0.08	0.05
Litter								
Aciphylla aurea	488.0	239.1	1.75	0.16	1.22	3.02	0.56	0.33
Chionochloa rigida	8470.3	4092.6	28.21	2.48	8.20	3.36	3.17	6.51
Other	7002.5	2835.8	60.57	5.34	35.03	9.77	8.17	6.85
Total above-ground	26861.6	12367.2	167.7	17.1	111.4	43.8	23.9	24.5
(SEM)	(1200.1)	(560.3)	(7.2)	(0.9)	(5.3)	(2.3)	(1.1)	(1.1)
Roots								
Aciphylla aurea	45.5	19.8	0.26	0.08	0.72	0.17	0.13	0.03
Beneath tussocks	8242.0	3699.3	50.90	4.23	16.17	1.54	1.97	7.88
Between tussocks	4644.7	2128.3	26.13	2.57	8.51	1.17	1.27	4.40
Total below-ground	12932.1	5847.4	77.3	6.9	25.4	2.9	3.4	12.3
(SEM)	(817.3)	(367.7)	(5.0)	(0.4)	(1.5)	(0.2)	(0.2)	(0.8)
Total above- and below-ground	39793.7	18214.6	245.0	24.0	136.8	46.7	27.3	36.9
(SEM)	(1175.7)	(538.1)	(7.3)	(0.7)	(4.6)	(2.3)	(1.0)	(1.1)

[a] Mostly *Agrostis capillaris* and *Anthoxanthum odoratum*.
[b] *Hieracium pilosella* and *H. lepidulum*.
[c] *Lycopodium fastigiatum* and *L. scariosum*.
[d] Mostly *Polytrichadelphus magellanicus*.

Appendix 3

PRE-BURN ASSESSMENT OF BIOMASS, CARBON AND NUTRIENT POOLS (kg/ha) AT THE MT BENGER STUDY SITE (APRIL 1998)

Values are the mean of five samples per plot and nine plots per site.

	BIOMASS	C	N	P	K	Ca	Mg	S
Grasses, rushes and sedges								
Adventive grasses[a]	722.7	326.3	6.51	0.71	3.38	0.40	0.76	0.80
Chionochloa rigida	5536.9	2595.6	36.09	4.97	48.60	2.04	4.13	4.17
Poa colensoi	278.5	125.7	2.54	0.27	1.17	0.13	0.29	0.38
Rushes and sedges[b]	41.3	19.0	0.44	0.05	0.30	0.03	0.06	0.06
Forbs								
Aciphylla hectori	11.6	5.3	0.15	0.02	0.25	0.09	0.05	0.01
Celmisia gracilenta	22.6	10.3	0.31	0.03	0.18	0.08	0.07	0.03
Hieracium spp.[c]	1.8	0.7	0.02	0.00	0.02	0.00	0.01	0.00
Isolepis aucklandica	66.2	28.2	0.75	0.06	0.37	0.03	0.08	0.08
Oreobolus pectinatus	190.5	86.8	1.58	0.17	1.02	0.08	0.23	0.14
Raoulia subsericea	34.8	16.4	0.34	0.04	0.21	0.15	0.09	0.05
Minor forbs	75.7	32.1	0.90	0.08	0.47	0.08	0.14	0.10
Shrubs								
Coprosma cheesemanii	12.2	6.2	0.10	0.01	0.04	0.05	0.01	0.01
Gaultheria depressa	31.0	14.9	0.25	0.03	0.14	0.10	0.06	0.03
Hebe odora	243.9	124.9	1.56	0.29	1.66	0.47	0.52	0.21
Acrothamnus colensoi	110.2	53.7	1.25	0.12	0.36	0.44	0.17	0.12
Leucopogon fraseri	93.6	45.6	1.06	0.10	0.30	0.37	0.15	0.10
Pentachondra pumila	268.1	134.9	2.09	0.16	0.70	1.02	0.37	0.20
Pernettya macrostigma	2.9	1.4	0.02	0.00	0.01	0.01	0.01	0.00
Minor shrubs	87.2	40.3	0.79	0.07	0.44	0.33	0.31	0.07
Lower plants								
Hymenophyllum sp.	27.8	10.0	0.30	0.03	0.29	0.02	0.05	0.03
Lycopodium spp.[d]	112.5	51.5	1.31	0.19	0.86	0.05	0.13	0.13
Coarse mosses[e]	1069.3	492.7	7.17	0.59	3.68	0.32	1.07	0.77
Fine mosses[f]	77.8	33.9	0.71	0.07	0.40	0.06	0.12	0.08
Lichen	41.5	17.9	0.34	0.03	0.14	0.01	0.03	0.03
Litter								
Aciphylla hectorii	3.4	1.6	0.02	0.00	0.02	0.02	0.02	0.00
Chionochloa rigida	16032.0	7671.3	52.98	3.90	14.44	6.66	8.19	8.79
Other	3855.7	1667.4	32.76	3.18	16.01	1.52	3.36	4.66
Total above-ground	9051.5	13614.8	152.4	15.2	95.5	14.6	20.5	21.1
(SEM)	(1550.5)	(751.1)	(5.8)	(0.6)	(4.2)	(1.0)	(0.9)	(0.9)
Roots								
Beneath tussocks	3291.5	1441.0	19.00	1.66	8.29	0.25	0.83	3.24
Between tussocks	6384.9	2426.3	53.38	4.92	31.17	2.02	4.97	7.02
Total below-ground	9676.4	3867.3	72.4	6.6	39.5	2.3	5.8	10.3
(SEM)	(694.7)	(271.9)	(5.5)	(0.5)	(3.1)	(0.2)	(0.5)	(0.8)
Total above- and below-ground	38727.8	17482.1	224.7	21.7	134.9	16.8	26.3	31.3
(SEM)	(1820.6)	(853.5)	(7.9)	(0.7)	(4.7)	(1.0)	(1.1)	(1.1)

[a] Mostly *Agrostis capillaris* and *Anthoxanthum odoratum*.
[b] Mostly *Carex wakatipu*.
[c] *Hieracium pilosella* and *H. lepidulum*.
[d] *Lycopodium fastigiatum* and *L. scariosum*.
[e] Mostly *Polytrichadelphus magellanicus*.
[f] Mostly *Leptotheca gaudichaudii*.

Appendix 4

WEATHER CONDITIONS, FIRE WEATHER INDICES AND FIRE BEHAVIOUR FOR TUSSOCK GRASSLAND FIRES AT DEEP STREAM AND MT BENGER

Plots are listed in the order in which they were burned.

	DEEP STREAM						MT BENGER					
	SPRING BURNS			SUMMER BURNS			SPRING BURNS			SUMMER BURNS		
	PLOT 3	PLOT 8	PLOT 4	PLOT 2	PLOT 5	PLOT 9	PLOT 9	PLOT 1	PLOT 6	PLOT 3	PLOT 5	PLOT 8
Weather conditions												
Temperature (°C)	19.3	21.4	18.3	18.0	18.2	18.7	7.8	9.5	10.8	11.2	12.1	11.9
Relative humidity (%)	41	43	51	59	59	60	70	65	57	73	68	70
Wind speed at 10 m (km/h)	17.4	23.2	25.3	24.8	26.6	21.8	11.1	16.7	18.1	8.1	12.4	11.0
Days since rainfall > 6 mm	4	4	4	10	10	10	2	2	2	2	2	2
Fire weather indices												
Fine Fuel Moisture Code (FFMC)	89.9	89.9	88.7	86.6	86.6	86.6	78.7	79.9	81.4	74.6	75.3	75.9
Duff Moisture Code (DMC)	14	14	14	26	26	26	6	6	6	5	5	5
Drought Code (DC)	20	20	20	204	204	204	33	33	33	178	178	178
Initial Spread Index (ISI)	10.1	13.6	12.6	9.2	10	7.9	1.7	2.6	3.3	1.1	1.5	1.4
Buildup Index (BUI)	14	14	14	39	39	39	9	9	9	9	9	9
Fire Weather Index (FWI)	11.8	14.9	13.8	18.4	19.6	16.4	1.0	2.3	3.2	0.6	0.8	0.8
Fire behaviour												
Flame length (m)	2.5	2.5	3.0	2.0	2.5	3.0	2.0	2.0	2.5	2.5	2.5	2.0
Rate of spread (m/h)	1100	1190	1830	350	460	1300	510	420	1040	1280	1540	800

What effect does fire have on tall-tussock grasslands?

The effects of early- and late-season fires on tall-tussock grasslands were examined at two sites in Otago. Fires reached high temperatures (> 1000°C), but were of short duration (4–8 minutes) and had little heating effect on the soil. Fires under damp spring conditions posed little threat to the long-term survival of the tall-tussock ecosystem. However, fires later in the season or under drier conditions resulted in higher plant biomass, carbon and nutrient losses, and much greater tiller and tussock mortality. Therefore, minimising the extent of fires under these conditions should be a priority wherever tussock cover is to be retained.

Payton, I.J.; Pearce, H.G. 2009: Fire-induced changes to the vegetation of tall-tussock (*Chionochloa rigida*) grassland ecosystems. *Science for Conservation 290*. 42 p.