Economic benefits of a recent research program into controlling serrated tussock in south-eastern Australia

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Summary

Serrated tussock (*Nassella trichotoma* (Nees) Arechav.) is an economically important weed in the temperate regions of south-eastern Australia. Serrated tussock causes heavy losses of pasture and livestock production, is costly to control, and imposes external costs through spread. The purpose of this paper is to evaluate the economic benefits of recent research into serrated tussock in Australia. Estimates were made of the annual costs of serrated tussock to wool producers and of the benefits from an increased level of research into control using cost data from the New South Wales and Victorian state governments. The mean annual opportunity costs of wool production foregone because of serrated tussock ranged between $81.6 million for the lowest (20%) weed content in the pasture to $226.5 million for the highest (50%) content. The incremental net present value of benefits of the recent research program into controlling serrated tussock had mean values of $63.3 million at the lowest weed content and $185.4 million at the highest content. Disaggregating the benefits between wool producers and consumers in different regions showed that although the gains to research into serrated tussock control could be high, the large economic welfare gains to the temperate region's wool producers had to be balanced against losses of economic welfare to wool producers in other regions.

Introduction

Serrated tussock (*Nassella trichotoma* (Nees) Arechav.), a native of the southern grasslands of South America, is the major perennial grass weed of temperate pastures in south-eastern Australia. Serrated tussock mainly occurs in eastern New South Wales and Victoria where average annual rainfall exceeds 600 mm and normal mean January temperatures do not exceed 21°C. Campbell (1977) considered serrated tussock to be Australia's most important pasture weed because it is unpalatable to livestock, it is hard to identify, it seeds prolifically and the seeds are readily dispersed, and it is costly to control, particularly in non-arable country. Because of its high neutral detergent fibre (86%) and low protein content (4%), serrated tussock has little grazing value and greatly reduces the carrying capacities of all temperate pastures. Heavily infested areas support only 0.5 dry sheep equivalents (DSEs) per hectare compared with 15 DSEs per hectare on improved perennial grass pastures (Campbell 1974). Serrated tussock is a prominent example of a plant that is in equilibrium in its native country but has become aggressive in Australian conditions where better quality pastures, less marked seasonal differences in pasture availability and lower stocking rates have favoured its persistence (Campbell 1998). Serrated tussock is proclaimed noxious in the Australian Capital Territory, New South Wales, Tasmania, South Australia and Victoria.

The main aspect of the economic problem with serrated tussock is that its presence in all types of pastures results in reduced stocking rates and large losses of livestock production. Also, controlling serrated tussock by replacement with introduced perennial grasses is expensive. This aspect has been a deterrent to investment in control and has enabled serrated tussock to spread and impose additional costs on other producers and communities. These issues have been the focus of previous studies that have evaluated the economics of control by livestock producers (Vere *et al.* 1993), the economics of government activity in control (Vere *et al.* 1980, Edwards and Freebairn 1982), and the external costs of serrated tussock spread (Jones *et al.* 2000). The main objective of those studies has been to improve the economic information available to assist in the private and public control of serrated tussock.

This paper has two objectives. The first is to estimate the annual economic cost of serrated tussock to the Australian wool industry in the temperate regions of south-east Australia using an economic modelling system that incorporates the private and social dimensions of the serrated tussock problem. Costs are estimated in terms of the values of wool production foregone due to serrated tussock for four infestation levels in which serrated tussock comprises between 20% to 50% of the pasture. The second objective is to estimate the economic benefits from recent research into serrated tussock control and to compare these benefits to recent research costs that have been incurred by the New South Wales and Victorian governments, the principal public agencies that have been involved in serrated tussock research. The focus region is the temperate areas of south-eastern New South Wales and Victoria in which serrated tussock research has been centred. This region contains most of all introduced pastures and carries nearly half the New South Wales and Victorian sheep and cattle populations. The evaluation has a regional and Australian wool industry focus because wool-growing is commonly practised throughout the region. Further reference to serrated tussock control is intended to imply serrated tussock research since research has determined the recommended control procedures.

The serrated tussock problem in the temperate regions

Area estimates

The threat of serrated tussock was first recognized in 1935 in southern New South Wales after its introduction in imported fodder from Argentina. By the 1950s the weed occupied large areas of south-eastern New South Wales. A survey of the serrated tussock problem on the New South Wales central tablelands found that many properties had heavy infestations and that much larger areas were threatened by the weed (Fallding 1957). Many producers were unable to control serrated tussock and most had abandoned control efforts in non-arable country. The average gross income from serrated tussock infested areas was estimated to be less that one-third of the income from pastures that were free of the weed.

Twenty years later, Campbell (1977) estimated that the total area of serrated tussock in New South Wales was 680 000 ha. Infestations were classified into three categories; dense in which animal production was seriously diminished, scattered patches with isolated plants that would soon become dense without control, and scattered plants with no heavy concentrations. Later surveys by Campbell (1987) and Gorham (1994, unpublished) found that the area of serrated tussock had declined by about 30% between 1977 and 1987, but by 1994 the infested area had increased by 9% over the 1977 level. Campbell (1987) attributed the release of the herbicide Tetrapion as the major reason for the decline in serrated tussock by 1987, but the increase in serrated tussock areas by 1994 was unexplained.

Jones and Vere (1998) used the data from the previous surveys to relate the serrated tussock problem to local soil fertility and rainfall conditions and to the production capability of the affected land in New South Wales shires. The re-estimated serrated tussock area was 887 000 ha of which 125 000 ha were heavily infested, 219 000 ha were moderately infested and 543 000 ha were lightly infested. The southern tablelands had the largest serrated tussock area (414 000 ha) of which 40% was in the Monaro region, while the central tablelands had 309 000 ha. The larger total infested area compared to the previous estimates was attributed to a likely underestimate by the earlier surveys of the actual extent of heavy and moderate infestations.

Serrated tussock is also a major problem in Victoria and was first reported there in 1954. By 1998, the weed occupied 130 000 ha which was a 430% increase in the area recorded in 1980. Serrated tussock was most prominent in the Corangamite (75 000 ha) and Port Phillip (29 000 ha) catchment management authority regions. The total area of serrated tussock infestations in 10 such regions was 105 000 ha (Morfe *et al.* 2002). Nearly one million ha in Victoria were considered to be at risk of infestation by serrated tussock (McLaren *et al.* 1998).

The value of good weed distribution information is that it enables the regional scale of a weed problem to be accurately defined and related to the livestock industries that operate within the region. In this instance, the temperate region annually contributes about 30% of Australian wool production and a similar proportion of beef cattle. The distribution data suggest that serrated tussock is having a significant economic impact on the regional livestock industries and that it will worsen over time if the problem is not reduced through continued research and the adoption of control recommendations.

Previous economic studies of serrated tussock

As indicated above, serrated tussock has been the subject of several previous economic studies. At the farm level, benefit-cost analysis (BCA) was used to determine the economic returns of controlling serrated tussock with improved pastures under a range of soil fertility and rainfall environments (Vere *et al.* 1993). The general result was that serrated tussock could be economically controlled in the long-term under conditions which favoured pasture growth and where pastures could support at least 5 DSEs per ha. Net benefits were highest in the most favourable soil fertility and rainfall environments because of the reduced time required for the replacement pasture to reach its full stocking potential. Control was uneconomic in low soil fertility and low rainfall environments where the discounted returns did not cover the long-term costs of pasture establishment and maintenance.

Broader-level economic analyses also have been undertaken because of the need to evaluate the benefits of public involvement in the serrated tussock problem through the research, extension and regulation activities of governments. One estimate of the social impact of serrated tussock in New South Wales valued the potential increase in wool production from control to be $60 million per annum (Vere *et al*. 1980). That estimate was revised by Edwards and Freebairn (1982) using an economic model that recognized that serrated tussock control resulted in productivity increases in that part of the national wool industry that it directly affected (the New South Wales tablelands), but not in the remainder of the industry. That model also recognized that wool was an internationally-traded commodity and the impacts of serrated tussock control in regional New South Wales would have economic effects on foreign wool producers and consumers because of Australia's dominant position in the world wool trade. At low wool price elasticities of supply and demand, regional wool producers gained ($160 million) and producers in other regions without the serrated tussock problem suffered losses ($144 million) from the wool price decrease. Australian wool consumers enjoyed only small gains (<$0.5 million) from serrated tussock control. This study demonstrated the value of using a disaggregated economic model to evaluate the social welfare benefits of adopting a biological technology such as serrated tussock control that only had application to a part of a national industry.

Other studies used improved weed distribution data to evaluate the serrated tussock problem (Jones and Vere 1998), and the external costs of serrated tussock spread in the low rainfall areas of south-eastern New South Wales (Jones *et al.* 2000). The first study determined that the widespread control of serrated tussock in New South Wales could generate annual benefits of $40.3 million to tablelands wool and lamb producers. In the second, Jones *et al.* (2000) evaluated the external cost associated with the spread of serrated tussock in south-eastern New South Wales where low rainfall and low soil fertility prevent economic control by pasture improvement. External costs indicate a divergence between the private and socially-desirable optimal levels of weed control and provides a *prima facie* justification for public intervention in weed control, such as had been proposed at that time for serrated tussock in the Monaro region. A stochastic simulation model was used to measure the costs of serrated tussock spread from an infested area to an adjoining clean area and to evaluate the economic benefits from three control options: periodic herbicide use in a naturalized pasture system, herbicide use followed by perennial pasture establishment, and herbicide use followed by the revegetation of the affected country with native trees. The third option was found to be socially optimal in minimizing the external cost from serrated tussock spread. Other non-agricultural benefits were reduced soil loss, a reduction in rising water tables with consequent beneficial dryland salinity effects, and the encouragement of a greater natural bio-diversity.

Morfe *et al.* (2002) estimated that a pro-active strategy of intervention in serrated tussock control by the Victorian government in the 10 catchment management authority regions that were affected by serrated tussock would yield benefits with 30-year present values of $5.8 million to $18.1 million under various livestock yield and price scenarios. Uncoordinated serrated tussock control in which the government's input was lacking generated long-term losses for all regions and scenarios, while a reactive control strategy produced a mixture of small gains and some large losses over the 30-year period.

In summary, previous economic research into the serrated tussock problem has concerned the on-farm benefits of control, the social costs of the weed and the external costs of its spread. This paper has a different focus: the evaluation of the benefits of recent public-funded research into the control of this weed in the temperate region.

Methods

The methods used to evaluate the economic benefits of serrated tussock research are based on the proposition that weeds cause annual economic costs to livestock producers and their industries, and reductions in these costs become benefits when weeds are controlled. Three types of models are used: a grazing systems model to determine the economic changes that result from serrated tussock in pastures, a social impact model to calculate the economic welfare effects of the weed on the producers and consumers of livestock commodities, and a benefit-cost model to evaluate the net benefits of research into controlling serrated tussock when the costs are known. The links between the models are that the first calculates the differences in livestock production costs from pastures containing varying levels of serrated tussock, the second uses these values to calculate the economic benefits from reducing serrated tussock in pastures, and the third compares these benefits against the costs of research that results in the serrated tussock reductions.

Serrated tussock restricts livestock production by reducing feed availability, thus its economic impact can be evaluated in terms of the value of livestock production foregone. Research has established that serrated tussock is most effectively controlled by replacement with improved pastures, in which legumes are sown to initially suppress weed seedlings and to improve soil fertility so as to enable the perennial grass component to quickly become dominant (Campbell 1998). Control in non-arable country is more difficult because pastures are less reliably established by aerial methods than under cultivation. These control practices were incorporated into a linear programming (LP) model of wool production based on temperate pastures that was used to determine the economic differences between optimal farm plans for pastures containing various levels of serrated tussock (Jones and Vere 1998). The model incorporates pasture groups based on introduced and native perennial grasses, legumes, annual grasses, broadleaved weeds and serrated tussock. Each group has a different total biomass, monthly dry matter production and feed energy supply. The preferred groups are the introduced perennial grasses and legumes. Weeds are undesirable because they take up an ecological space that could be occupied by a more valuable plant. Variations in soil fertility and rainfall are represented by differences in the annual dry matter production from each pasture group.

Serrated tussock levels were modelled as being between 20% (ST1) to 50% (ST4) of the total pasture content (Table 1). The base, or weed-free pasture, comprised a high proportion of introduced perennial species and no serrated tussock. While there are no precise measurements of actual levels of serrated tussock in the region's pastures, the specified levels were considered to represent typical degrees of the serrated tussock problem in the region. The main use of the LP model was to calculate the reductions in the costs of wool production that could result from reducing serrated tussock in the pasture. This is the commonly-adopted base measure of the benefits of an agricultural research process that generates a production-increasing technology (Alston *et al*. 1995). When expressed as a proportion of the average wool price, these calculations are the reductions in the unit wool production costs that result when serrated tussock is controlled by pasture improvement. The calculations also represent the regional wool supply shift values and correspond to the research-induced cost saving (Alston *et al*. 1995).

The social impact model recognizes that wool producers in aggregate form a wool industry, and the welfare costs of serrated tussock to all producers are the costs of the weed to the industry. This type of model follows the concept of economic surplus that has been widely used to evaluate the welfare effects of the adoption of new agricultural technologies such as serrated tussock control. Producers incur an economic surplus or welfare loss from the restricted production, while consumers incur a similar loss from the commodity's higher price. Weed control leads to production increases that are represented by an outward shift of the commodity's supply function, which in turn leads to a price fall. Producers gain from the expanded production and consumers gain from the lower price. The benefits from weed control are distributed between producers and consumers according to the price elasticities of supply and demand.

Table 1. Pasture and serrated tussock combinations (ST) and annual costs of serrated tussock.

	Serrated tussock level in pasture				
	Base	ST 1	ST 2	ST 3	ST 4
Pasture components (%)					
Perennial grass	60	50	50	40	30
Legume	40	30	20	20	20
Serrated tussock	0	20	30	40	50
Annual cost of serrated tussock ($m.) [A]		81.6	113.3	155.4	226.5
Marginal benefit from control ($ per ha) [B]		3.75	4.06	5.30	5.98

[A] Mean aggregate costs to wool producers in the temperate region; calculations made using the R statistical package (2003).

[B] Marginal benefit to serrated tussock-affected wool producers of a 1% reduction in serrated tussock and replacement with improved perennial grass (e.g., from 20% to 19% in ST1).

This model is based on the assumption of a parallel shift of the commodity's supply function so that the production cost reductions are uniform across the industry. In application, this assumption is restrictive because many agricultural production problems (such as serrated tussock in pastures) are geographically specific and relate more-so to regions than to whole industries. A regionally-disaggregated economic surplus model is appropriate to use where a weed problem occurs in one region and not in others as it recognizes that all producers in an industry are not similarly affected by the problem and are likely to have different production cost structures (Edwards and Freebairn 1982). This implies that the effects of a production-increasing (or cost-reducing) technology will vary across the regions that are parts of a national industry. The main features of the disaggregated model are that price is the same in each region and the regional variations in production result in different production costs that are indicated by the different sloping segments of the national supply curve.

Two Australian regions were defined: the temperate region to represent the areas in which serrated tussock is a problem, and the rest of Australia in which wool production is not directly affected by the weed. In the temperate region, serrated tussock restricts wool production and so causes economic welfare losses to regional wool producers. Wool producers outside the temperate region benefit from higher prices that result from the restricted production. Controlling serrated tussock reverses these welfare effects whereby temperate region wool producers benefit from increased production but other wool producers lose from the reduced price. All wool consumers benefit from the lower price. The international wool market was also included as a third region because of Australia's importance as a wool exporter. Price changes from the presence and control of serrated tussock in the temperate region have economic welfare effects on wool producers and consumers in other countries that are similar to those in the rest of Australia. Table 2 contains the values of the medium-term wool supply and demand elasticities, and the wool industry quantities and prices that were used in the economic surplus change calculations. No regional wool consumption was considered after Edwards and Freebairn (1982).

For the BCA, the benefits from research into the control of serrated tussock for the four specified infestation levels were held to be equal to the annual changes in economic welfare from the outward shift of the wool supply function. An important issue in this process was to distinguish the recent research program into the serrated tussock problem from that research which has been previously undertaken. Thus the with-research scenario is the expected impact on the wool industry from recent investment in serrated tussock research, while the without-research scenario represents the impacts flowing from the past research investments that have been made. This distinction enabled the expected research benefits to be measured as the difference in the economic returns between the two scenarios, or the marginal or incremental economic benefit from the current research that was net of any ongoing benefits from past research investment and net of the expected benefits from alternative serrated tussock research that might be implemented in the absence of the current research investment.

It has been proposed that the main impacts of new investment in weeds research is to expedite the delivery and adoption of the research outcomes (CIE 2001). This proposition implies that new research represents an addition to an investment baseline, and that the incremental net benefits should be measurable primarily in terms of differences in the impacts of adoption lags and rates. This is particularly relevant in the serrated tussock research context because this weed problem has been investigated for many years (Campbell and Vere 1995) and continues to attract research funding. The current evaluation is based on the assumption that the new investment increased the intensity of serrated tussock research. The effect of this investment has been to generate shorter lags in delivering the outcomes and higher levels of adoption of the outcomes by wool producers. Following the approach of Vere *et al.* (2003), the with research scenario represents the investment in serrated tussock research that has been made by the New South Wales and Victorian state governments in recent times. Alternatively, the without research scenario is assumed to represent the hypothetical case of no such investment.

The main factors that determine the benefits from serrated tussock research are the expected efficiency of the control methods and their anticipated level of adoption by wool producers. The first factor influences the size of the supply shift because serrated tussock control increases pasture availability and stocking rates and reduces the unit costs of wool production. It was considered that both scenarios would deliver equally efficient control methods since it was likely that the same researchers would be involved in each case. Each scenario therefore had the potential to generate equal supply shift values. It was also recognized that factors such as climatic and price cycles that introduce uncertainty into the realization of the research benefits over time would have greater impacts on the without-research scenario because it had longer research and adoption lags. These considerations then enabled the two research scenarios to be distinguished by differences in their respective research lags and outcome adoption profiles. Pannell (1999) noted that one of the main benefits of research that provides improved information on an existing technology is the more rapid adoption of the outcomes. This observation is consistent with the with-research scenario that has been assumed in this serrated tussock research evaluation.

Table 2. Values used in economic surplus analysis.

	Temperate region	Rest of Australia	Rest of world
Wool production (kt)	182	580	1908
Wool consumption (kt)	0	18.3	2650
Wool supply elasticity	0.35	1.4	1.5
Wool demand elasticity	0	-0.8	-4.0
Wool price (cents/kg)	750	750	750

Sources: Wool quantities and price, ABARE (2003); elasticities, Griffith *et al.* (2001a, 2001b).

Table 3. Triangular probability distributions values for the random variables.

	Maximum	Mode	Minimum
Supply shifts (%)[A]			
ST1	0.12	0.073	0.05
ST2	0.15	0.118	0.07
ST3	0.20	0.163	0.10
ST4	0.30	0.223	0.15
Adoption ceiling (%)			
With-research scenario	30	25	15
Without-research scenario	25	20	10
Adoption lag (years)			
With-research scenario	6	4	2
Without-research scenario	8	6	4
Wool price ($/kg)	9	7.5	5

[A] Reduction in the cost of wool production per kg as proportion of wool price.

The foregoing issues were incorporated in the evaluation by specifying the supply shifts, the adoption rates and lags and the price of wool as random variables derived from triangular probability distributions of their minimum, modal and maximum values. Since each of these variables is a critical factor in determining the levels of research benefits, allowing their values to vary enabled the economic surplus changes to be simulated within the defined probability distributions. The distribution of values for these variables are given in Table 3 for each scenario.

As previously indicated, the values of the wool supply shifts were calculated using the LP model. For the adoption factors, the long history of serrated tussock research and the persistence of the problem suggests that the main source of benefit uncertainty was most likely to be the adoption of the research outcomes (some reasons for this are discussed below). Low adoption is most apparent in areas where pasture improvement is difficult (Jones *et al.* 2000). Because such country comprises a large proportion of the total area that is most affected by serrated tussock (Jones and Vere 1998), the probability distribution values of the ceiling adoption levels for the serrated tussock control technology under the with-research scenario were specified to be 30% maximum, 20% mode and 10% minimum to reflect the apparent low adoption of the control recommendations. The corresponding values for the adoption lags were two years minimum, four years mode and six years maximum. For the without-research scenario, the ceiling adoption levels were reduced by 5% from those for the with-research scenario, and the adoption lags were increased by two years. The values for the probability distributions for the adoption random variables were set after discussions with staff who have been mainly responsible for the serrated tussock research in New South Wales (M.H. Campbell personal communication 2004), and were considered to realistically define the limits of each variable's likely value distribution. Wool prices were varied between $5 to $9 per kilo. Each of the four random variables were simulated over 10 000 iterations in a

Monte Carlo simulation model developed using the R statistical package (R Development Core Team 2003).

Research costs for the with-research scenario were based on estimates of recent expenditure by the New South Wales and Victorian governments. In 2000–01, expenditure by NSW Agriculture on pasture weed research totalled $2.12 million (NSW Agriculture, unpublished accounts 2002). As this cost was not itemized according to weed species, it was assumed that since serrated tussock is the principal noxious weed in New South Wales, 20% of the cost ($0.434 million) was allocated to research into serrated tussock. The Victorian Department of Natural Resources and Environment allocated a similar amount of $0.423 million per annum for the same purpose over the three-year period 1999–2001 (D.A. McLaren personal communication 2003). A total one-year cost of $0.847 million was held to be the representative cost of recent research into serrated tussock by government and was assumed to be incurred in each of the first five years of the BCA period (2003–2007). No further research costs were incurred thereafter but $0.2 million per annum was allowed for the costs of extending the outcomes of the research over the remaining period (2008–2022) by both state governments. There were no research costs for the without-research scenario but the same extension costs were assumed to apply. Benefits were estimated for 10 percentage point reductions in the level of the weed in the pasture for each of the infestation levels ST1 to ST4. In ST1, serrated tussock was reduced from 20% to 10% of the pasture content, from 30% to 20% in ST2, from 40% to 30% in ST3 and from 50% to 40% of pasture content in ST4. Benefits were projected over a 20-year period (2003–2022) and converted to net present values (NPVs) using a 5% discount rate. Benefit-cost ratios (BCRs) were also calculated from the discounted benefits and costs.

Table 4. Annual economic surplus change results from alternative serrated tussock infestation scenarios ($m).

	Serrated tussock level in pasture			
	ST 1	ST 2	ST 3	ST 4
Regional producers' surplus change				
Maximum	142.12	183.36	245.72	361.95
Mean	81.57	113.32	155.42	226.53
Minimum	40.21	53.91	75.82	114.04
Standard deviation	17.47	21.40	27.77	41.10
ROA producers' surplus change				
Maximum	-33.63	-45.22	-63.81	-96.56
Mean	-68.48	-95.51	-131.67	-193.61
Minimum	-119.80	-155.17	-209.20	-311.77
Standard deviation	14.77	18.18	23.77	35.68
ROW producers' surplus change				
Maximum	-127.42	-171.33	-241.85	-366.15
Mean	-259.49	-362.05	-499.36	-734.82
Minimum	-454.14	-588.40	-793.73	-1184.06
Standard deviation	56.01	68.97	90.24	135.60
ROA consumers' surplus change				
Maximum	4.32	5.58	7.49	11.10
Mean	2.47	3.44	4.73	6.92
Minimum	1.22	1.63	2.30	3.47
Standard deviation	0.53	0.65	0.85	1.26
ROW consumers' surplus change				
Maximum	639.43	831.31	1127.33	1698.52
Mean	364.08	509.72	706.24	1047.13
Minimum	178.20	240.16	340.06	517.55
Standard deviation	79.09	97.81	128.77	195.81
Total annual economic surplus change				
Maximum	211.93	276.68	377.61	575.75
Mean	120.14	168.92	235.35	352.16
Minimum	58.67	79.16	112.51	172.35
Standard deviation	26.31	32.70	43.38	66.90

Calculations made using a stochastic simulation model developed within the R statistical package (2003).

Results

The results of the LP modelling (Table 1) indicate that serrated tussock causes substantial annual costs to wool producers in the temperate region. When assessed in terms of the value of wool production foregone from its presence in pastures, the mean annual costs of serrated tussock in the temperate region were between $81.6 million for the low content level (ST1) to $226.5 million for the highest level content in ST4. The main factor that determines the size of these costs is the extent to which the serrated tussock growth curve coincides with those of the desirable pasture species. Serrated tussock provides no grazing value at any stage of its growth cycle and the opportunity costs of this weed are much higher than those of other pasture weeds, such as annual grasses and broadleaved weeds that do provide periodic grazing value. The impact of serrated tussock on feed availability is measured by the supply shift value at each infestation level that is calculated using the LP model (Table 3). These values increase threefold between ST1 and ST4 and are relatively large because serrated tussock results in a total loss of desirable pasture dry matter production. Because these values also mirror the increases in production costs that result when serrated tussock is uncontrolled, costs are fully borne by the affected producers.

Table 4 contains the estimates of the annual economic surplus changes for wool producers and consumers in the three regions. These changes are equal under the two research scenarios because it was assumed that both scenarios generated an equally effective technology for controlling serrated tussock. On the production side, regional wool producers annually gain economic surplus valued a minimum $40.2 million under ST1 to a maximum $361.9 million under ST4. The mean values of the regional producers' surplus changes indicate that the most likely benefit levels are between $81.6 million to $226.5 million per annum across the four scenarios. These benefits are equivalent to the values of the mean annual production losses caused by serrated tussock that are prevented by control. Wool producers in the other two regions annually lose

Table 5. Stochastic 20-year BCA results for serrated tussock research; comparison of with- and without-research scenarios[A].

	Serrated tussock level in pasture			
	ST 1	ST 2	ST 3	ST 4
With-research scenario				
Net present values ($m)				
Maximum	442.57	519.55	725.71	1091.24
Mean	170.82	242.63	340.38	512.59
Minimum	55.90	84.26	120.42	181.85
Standard deviation	48.91	63.73	85.42	131.35
Benefit-costs ratios ($:1)				
Maximum	72.85	85.35	118.82	178.16
Mean	28.73	40.39	56.26	84.22
Minimum	10.08	14.68	20.55	30.52
Standard deviation	7.94	10.34	13.87	21.33
Without-research scenario				
Net present values ($m)				
Maximum	258.75	340.37	474.90	705.07
Mean	107.57	153.23	215.99	327.14
Minimum	30.96	39.27	77.20	104.75
Standard deviation	32.45	41.58	56.91	86.72
Benefit-costs ratios ($:1)				
Maximum	42.52	55.62	77.22	114.15
Mean	18.26	25.29	35.66	53.50
Minimum	5.96	7.30	13.39	17.81
Standard deviation	5.21	6.67	9.13	13.92
Benefits attributable to research				
Net present values ($m)				
Maximum	183.82	179.18	250.80	386.17
Mean	63.25	89.41	124.41	185.44
Minimum	24.94	44.99	43.21	77.10
Standard deviation	16.46	22.15	28.51	44.80
Benefit-costs ratios ($:1)				
Maximum	30.3	29.7	41.6	64.0
Mean	10.5	14.8	20.6	30.7
Minimum	4.1	7.4	10.2	12.7
Standard deviation	2.7	3.7	4.8	7.4

Calculations based on the total annual economic surplus change (Table 4) using a stochastic simulation model developed within the R-statistical package (2003); discounted at 5%.

significant amounts of economic surplus because they are unable to adopt the cost-reducing serrated tussock control technology but face a reduced wool price from the regional supply shift. Wool consumers in the ROA and ROW regions benefit from serrated tussock control research as a result of the increased quantities of wool available and the lower wool prices that have to be paid. The consumer benefit shares in the two regions are in proportion to the relative quantities of wool consumed and the values of the wool demand elasticities. The total annual benefit is the balance of the welfare gains to regional wool producers and to all wool consumers against the welfare losses incurred by wool producers in other regions and has mean values between $120.4 million to $352.2 million. These latter estimates are the benefit side of the BCA and are consistent with the general effects of the supply and demand elasticities on the distribution of benefits wherein regional wool supply is inelastic relative to its demands on the Australian and international markets. It should be noted that the maximum and minimum values here are the extreme values for each simulation of the total economic surplus change and are not the sum of the corresponding values for each of the elements of that measure.

A 20-year BCA was undertaken to determine the economic impact of the with- and without-research scenarios (Table 5). Under each research scenario, the NPV and BCR estimates indicate that reducing serrated tussock by adopting the research outcomes could generate substantial long-term economic benefits. Benefits are larger under the with-research scenario because they occur earlier in the BCA period and at higher adoption levels, and are less reduced by the discounting. The increase in benefit attributable to the research is the difference between the two sets of benefit estimates. The mean values of the NPVs of the incremental benefits are between $63.3 million when serrated tussock comprised 20% of the pasture biomass increasing to $185.4 million at the 50% level serrated tussock. In each instance, the benefits resulted from a 10 percentage point reduction in serrated tussock in the pasture. The mean BCR values for the incremental benefits over the four serrated tussock content levels are 10.5:1 to 30.7:1. This potential benefit increase is attributable to the increased research investment under the with-research scenario that expedites the generation of the research outcome and its adoption by wool producers.

Discussion

This paper presents estimates of the annual economic costs of serrated tussock in the temperate pasture areas of south-eastern Australia and of the long-term benefits of recent research into its control. The latter are the total benefits that could result from that research into reducing serrated tussock over a range of incidence levels in pastures. These benefits are attributed to the maintenance of a public research investment that enables an increased research effort and expedites the generation and extension of control recommendations to affected producers. Because it has not been possible to quantify the total costs incurred by all Australian research institutions in serrated tussock research over the years, recent indicative costs that have been incurred by the departments of agriculture of New South Wales and Victoria have been used in lieu. Since these two institutions have been most prominent in serrated tussock research, it is considered that the estimated incremental benefits can be realistically ascribed to that research investment.

The results indicate the potential for large long-term economic benefits from continued research into more effective serrated tussock management. In each research scenario, the reason for the high levels of potential benefits is that replacing serrated tussock with improved species results in proportionally greater increases in pasture and livestock production than replacing other pasture or weed species since serrated tussock provides no nutritive value to livestock. In essence, serrated tussock control enables production where it had not been previously possible. Differences occur in the supply shifts between the four scenarios because the marginal benefit of replacing a unit area of serrated tussock with a unit of improved pasture is larger when the weed comprises a high proportion of the pasture biomass than at lower proportions. Hence, a marginal increase in feed availability is of greater economic value in wool production from a pasture with a high serrated tussock content. These values are calculated directly by the LP model in which pasture improvement options were incorporated as activities and their costs were included in the model's optimization process when the replacement of the specified levels of serrated tussock with improved pastures is simulated.

Serrated tussock remains an important economic problem in the temperate region despite the long history of weeds research and extension and economic analyses that have demonstrated the long-term benefits that can result from its control. Over 20 years ago, Campbell's (1977) survey of 21 New South Wales shires reported that serrated tussock persisted because many producers lacked finance or skills, but most lacked the effort to control the weed. Other constraining factors were an ignorance of control recommendations and the use of ineffective control methods. The difficulties of controlling serrated tussock in environments unfavourable for pasture improvement were highlighted. While there have been no more recent surveys of these factors specific to serrated tussock, weeds remain the major problem faced by producers in maintaining the productivity of temperate pastures (Reeve *et al.* 2000). The earlier observations are likely to remain relevant today.

One reason for the persistence of the serrated tussock problem is that pasture improvement is expensive at $220 per ha under cultivation and $190 per ha by air (NSW Agriculture 2002). Serrated tussock can be economically controlled where rainfall and soil fertility favour perennial pasture establishment and stocking rates can be increased to more than the 5 DSEs per ha which is the minimum stocking capacity required for profitable long-term control. Most serrated tussock in the temperate region occurs in areas where the average stocking potential on improved pastures is at least 10 DSEs per ha. In these areas, the financial returns to control have been estimated to be large enough to withstand adverse changes in costs and prices over time (Vere *et al.* 1993). Pasture improvement is more risky in less favourable environments in which the problems of serrated tussock are accentuated. Control has been found to be uneconomic in low fertility-low rainfall country where the external cost problems associated with serrated tussock spread are most prominent (Jones *et al.* 2000). In areas such as the eastern rain shadow of the Snowy Mountains, the most practical control options for many problem areas of serrated tussock are alternatives to livestock production. Jones *et al.* (2000) suggested that natural revegetation was the most socially desirable solution to the problem of serrated tussock in such country.

This analysis has focused on the broad implications of public research into serrated tussock. The methods that have been used recognize that the presence and control of this weed in the temperate region can have important economic effects on all participants in livestock commodity markets, not just on the weed-affected producers. These results show that the adoption of the research outcomes into controlling serrated tussock will benefit temperate region wool producers and all wool consumers, while wool producers in other regions lose economic welfare from lower wool prices. The latter result suggests that it would not be in the interests of woolgrowers outside the temperate region to have serrated tussock controlled, even at the relatively low 10 percentage point reductions that have been modelled. The main implications of these results is that serrated tussock at any level in Australia's south-eastern temperate pastures causes large annual costs to wool producers and that the BCA estimates support the value of the research that has been undertaken into its control.

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